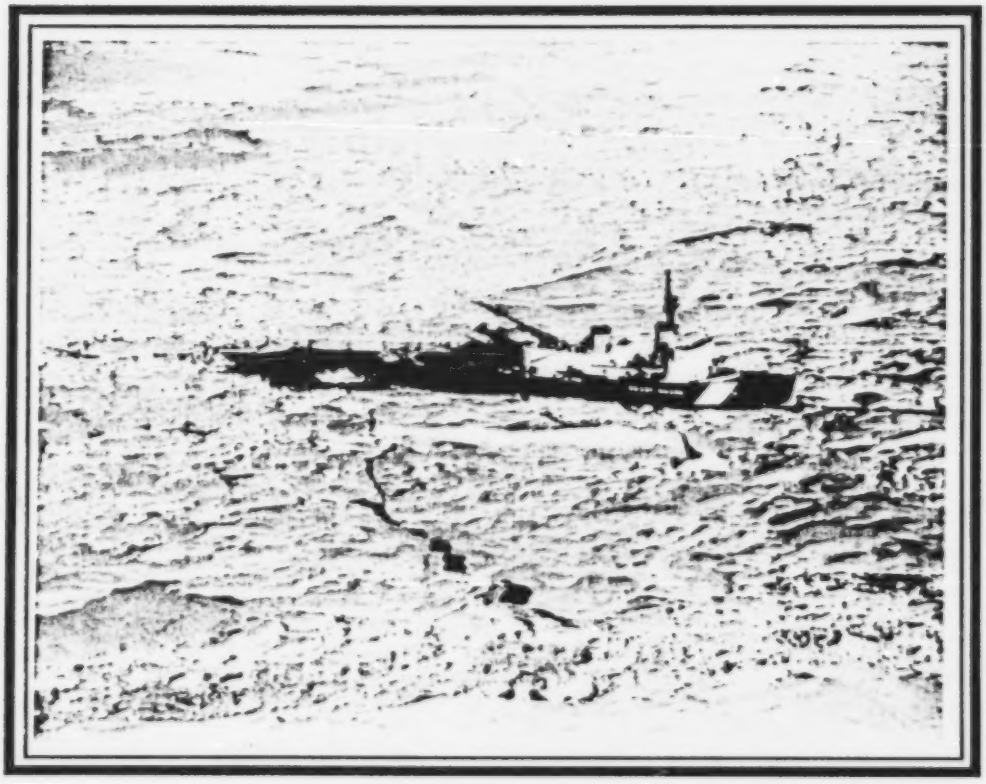
A Summary of the Results of the Canadian Participation in the Polar Class Trafficability Program

1981 - 1985

TP No.7471E
October 1986



Prepared for

TRANSPORTATION DEVELOPMENT CENTRE

ARCTEC CANADA LIMITED FR1723.C1

A SUMMARY OF THE RESULTS OF THE CANADIAN PARTICIPATION IN THE POLAR CLASS TRAFFICABILITY PROGRAM 1981 - 1985

TP 7471E

OCTOBER 1986

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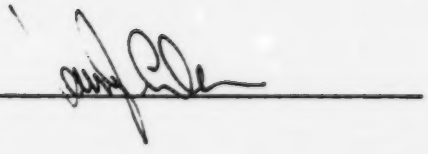
APPROVED BY: 

Transport Canada / Transports Canada

Development / Développement

REPORT DOCUMENTATION FORM

1 Transport Canada Report No.	2 TDC Project No	3 Recipient's Catalogue No.
TP 7471E	6321/6322/6323	

4 Title and Subtitle	5 Report Date
A Summary of the Results of the Canadian Participation in the Polar Class Trafficability Program 1981 - 1985	October 1986
	6 Performing Organization Report No FR1723C.1
7 Author(s) I.F. Glen, B. Menon, T. Roots	8 Transport Canada File No D1460-181-1
9 Performing Organization Name and Address Arctec Canada Limited 311 Legget Drive Kanata, Ontario K2K 1Z8	10 DSS File No 11SD.T8200-4-4546
	11 DSS or Transport Canada Contract No OSD84-00234
12 Sponsoring Agency Name and Address Transportation Development Centre (TDC) 200 Dorchester Blvd. West Suite 601, West Tower Montreal, Quebec H2Z 1X4	13 Type of Report and Period Covered
	14 Sponsoring Agency Code
15 Supplementary Notes	16 TDC Project Officer Ian Bayly

17 Abstract

This report contains a review of Canadian research conducted from 1981 to 1985 on the loads on and responses of ship hull structures and appendages in ice, based on data from dedicated full-scale trials on U.S. Polar Class icebreakers in the Arctic and the Antarctic. In this review, a complete account of the data collected in each year's trials is given, identifying what parts of the data have been analyzed along with what further analysis is required. The report covers the principal subject areas addressed by the Canadian research program: Structural Loads and Response of Appendages, including Steering Gear and Manoeuvring Performance in Level Ice. The results of the work have led to a greater understanding of the dynamic response of icebreaker hulls, propulsion system and steering gear to ice impact, and provided a full-scale data base. As well as providing specific performance data for the vessels in thick level ice, the manoeuvring tests have been used to develop semi-empirical mathematical models for turning in ice.

18 Key Words	19 Distribution Statement
Polar Class, Ship Structure, Rudders and Steering Gears, Ice Loads	A limited number of copies are available from the Transportation Development Centre.

20 Security Classification (of this report)	21 Security Classification (of this page)	22 No. of Pages	23 Price
Unclassified	Unclassified	60	-

TDC CDT 79-005
Rev 86

Canada

Transports Canada / Transport Canada

Développement / Development

FORMULE DOCUMENTAIRE DU RAPPORT

1. N° du rapport Transports Canada	2. N° de l'étude — CDT	3. N° de catalogue du destinataire
TP 7471E	6321/6322/6323	

4. Titre et sous-titre	5. Date du rapport
A Summary of the Results of the Canadian Participation in the Polar Class Trafficability Program 1981 - 1985	octobre 1986
	6. N° du rapport de l'organisme exécutant: FR1723C.1
7. Auteur(s): I.F. Glen, B. Menon, T. Roots	8. N° de dossier Transports Canada: D1460-181-1
9. Nom et adresse de l'organisme exécutant: Arctec Canada Limited, 311 Legget Drive, Kanata, Ontario, K2K 1Z8	10. N° de dossier — ASC: 11SD.T8200-4-4546
	11. N° de contrat — ASC ou Transports Canada: OSD84-00234
12. Nom et adresse de l'organisme parrain: Centre de développement des transports (CDT), 200 ouest, boul. Dorchester, Suite 601, tour ouest, Montréal, Québec H2Z 1X4	13. Genre de rapport et période visée
	14. Code de l'organisme parrain
15. Remarques additionnelles	16. Agent de projet — CDT: Ian Bayly

17. Résumé

Ce rapport rend compte de la participation canadienne au programme de recherche qui s'est déroulé de 1981 jusqu'au milieu de 1985 à bord de brise-glace de type Polar appartenant à la Garde côtière des Etats-Unis et concernait le comportement de leur coque, appendices compris, dans les glaces arctiques et antarctiques. Il recense les données obtenues durant chacune des années du programme de recherche, distinguant entre celles déjà dépouillées et celles dont une deuxième analyse pourrait se révéler fructueuse. Il traite des principaux secteurs ayant constitué la participation canadienne à ce programme de recherche, à savoir: comportement de la coque et des appendices, y compris la timonerie, dans les glaces et qualités manoeuvrières dans des glaces uniformes. Ce programme de recherche a débouché sur une meilleure compréhension de l'action des glaces sur les coques, l'appareil de propulsion et l'appareil à gouverner et sur leur tenue à la charge des glaces, tout en permettant de constituer une base de données très utile dû au fait qu'elles résultent d'essais en vraie grandeur. En plus d'avoir permis de caractériser les qualités manoeuvrières des navires considérés dans des glaces uniformes de forte épaisseur, les essais de manoeuvres dans les glaces ont débouché sur des modèles mathématiques semi-empiriques figurant la résistance à l'avancement en mode giratoire.

18. Mots-clés	19. Diffusion
brise-glace Polar, coque, appareil à gouverner, charge des glaces, gouvernail	Le CDT dispose d'un nombre limité d'exemplaires.

20. Classification de sécurité (de ce rapport)	21. Classification de sécurité (de cette page)	22. Nombre de pages	23. Prix
Non classifié	Non classifiée	60	-

CDT/TDC 79-005 Rev 86

Canada

SUMMARY

This report summarizes the accomplishments of four years of research onboard the USCG Polar Class icebreakers sponsored by Transport Canada. The research programs represent Transport Canada's participation in a large-scale program that has entered its sixth year, sponsored by a number of U.S. government agencies, principally U.S. Maritime Administration and U.S. Coast Guard, and by the companies of the Arctic Oil and Gas Association.

The modal objectives of the program were to provide a scientific basis for design, operating, and regulatory criteria applicable to navigation in Canadian Arctic waters, and the specific project objectives covered a number of technical aspects of ship response in ice.

The objectives were met by a series of full scale testing programs onboard the USCG icebreakers POLAR SEA and POLAR STAR in winter and summer ice conditions in the Arctic and the Antarctic.

The Canadian sponsored projects, conducted between 1981 and mid-1985, covered the measurement of hull girder dynamic response in ice, local structural loads, rudder and steering gear loads and manoeuvring characteristics in thick level ice. Additionally, as part of the program, research reports were made available to Transport Canada which included a large amount of environmental data, trafficability studies, level ice and bollard pull tests. These are reported separately.

Hull structural acceleration response tests provided useful data on the dynamics and vibratory characteristics of the hull of the vessels, and how it is excited under various ship/ice interactions. The dynamic behaviour of the shafting was also investigated.

A system of 80 strain gauge sensors fitted to the port bow of POLAR SEA to measure local impact loads, pressures and areas proved extremely successful due to the uniform nature of the hull structure and the technique used to relate strains to loads. The full-scale calibration of the "panel" accurately validated the mathematical model of the stucture, and the result has been the collection of a large quantity of ice load data in a variety of ice conditions including thick level ice in the Antarctic, multi-year ice and broken ice. Data has been collected over three consecutive years with this system.

The measurement of steering gear and rudder loads project complemented the analysis of data from previous trials and resulted in the development of a mathematical model to predict ice loads on rudders as a function of ice characteristics, ship speed, and steering parameters. A rudder and steering gear design procedure is presented.

The results of the manoeuvring trials, in addition to providing specific performance data for the Polar Class in thick (2 m) ice, have provided data on the relative turning characteristics in ice and open water, and helped to calibrate two separate forms of manoeuvring prediction models. A greater understanding of the interaction of ice forces on the hull and their influence on turning was obtained.

The report presents the results of the Canadian part of the six-year program, and in so doing provides an index of all reports which have resulted and their sources. In addition, the report identifies data that has been collected but not analyzed or that justifies further analysis in the light of newly acquired knowledge, and makes recommendations regarding further work.

SOMMAIRE

Ce rapport récapitule les travaux de recherche conduits durant quatre ans à bord de brise-glace de type Polar appartenant à la Garde côtière des Etats-Unis. Les travaux étaient organisés et financés par Transports Canada à titre de participation du Canada à l'ambitieux programme de recherche parrainé par des organismes américains comme l'US Maritime Administration et l'US Coast Guard, et par des entreprises privées appartenant à l'Arctic Oil and Gas Association. Ce programme de recherche en est maintenant à sa sixième année.

L'objet de ce programme a été de dégager les bases scientifiques sur lesquelles asseoir les calculs de résistance des coques, les modes d'exploitation et la réglementation de la navigation dans les eaux arctiques du Canada, ainsi que d'étudier le comportement des navires dans les glaces.

Le programme de recherche a comporté un certain nombre d'essais en vraie grandeur à bord des brise-glace Polar Sea et Polar Star, dans les eaux de l'Arctique et de l'Antarctique, dans des conditions glacielles propres aux saisons d'été et d'hiver.

La participation canadienne qui s'est déroulée de 1981 jusqu'au milieu de 1985 a comporté des essais concernant la réponse dynamique de la poutre-coque, la mesure des charges localisées des glaces et de la charge sur les appareils à gouverner et, enfin, la détermination des qualités manoeuvrières dans des glaces épaisses uniformes. En outre, Transports Canada a été informé du résultat de plusieurs recherches, sous la forme de rapports techniques sur l'environnement, la navigabilité des eaux arctiques et antarctiques, la résistance à l'avancement dans des glaces uniformes et la traction au point fixe, chaque rapport étant publié séparément.

Les essais concernant la réponse dynamique aux efforts ont permis d'approfondir les caractéristiques dynamique et vibratoire de la coque de ces navires, en mettant en évidence l'effet de la charge des glaces tant sur les coques que sur la ligne d'arbre.

Pour mesurer les charges localisées des glaces, un panneau comportant un réseau de 80 extensomètres a été fixé à l'avant bâbord du Polar Sea, cette technique ayant réussi à mettre en évidence la distribution des pressions surfaciques sur la coque ainsi que la corrélation entre charges et déformations, grâce à la nature uniforme de la charpente de ce navire. L'étalonnage de ce "panneau" en vraie grandeur a débouché sur la validation du modèle mathématique figurant le comportement théorique des coques. Par conséquent, les données amassées au cours des trois années consécutives constituent une documentation fiable, abondante et précieuse sur le comportement des coques dans des conditions glacielles très variables, y compris des glaces de plusieurs années, des glaces fragmentées et des glaces épaisses uniformes de l'Antarctique.

La mesure des charges exercées sur l'appareil à gouverner a été le prolongement des travaux d'analyse de données résultant d'essais antérieurs et a débouché sur la mise au point d'un modèle mathématique permettant de calculer la charge des glaces sur le gouvernail en fonction des caractéristiques de ces glaces, de la vitesse de marche et des paramètres propres à l'appareil à gouverner. Elle a permis, en outre, l'élaboration de lignes directrices applicables à l'étude de timoneries devant équiper les brise-glace.

Les essais de manoeuvre dans les glaces, en plus d'avoir permis de caractériser les qualités manoeuvrières des brise-glace considérés dans des glaces de 2 mètres d'épaisseur, ont renseigné sur leurs performances giratoires tant en eau libre qu'en eau chargée de glaces, et ont débouché sur le calage de deux modèles distincts figurant la résistance à l'avancement. En plus, les chercheurs ont obtenu une meilleure compréhension de l'action des glaces sur la coque durant les manoeuvres de giration.

Le rapport donne le résultat de la participation canadienne à ce programme qui dure depuis six ans et recense, sous la forme d'un index, tous les rapports qui ont été publiés ainsi que leurs auteurs. Il renseigne également sur les données amassées mais non dépouillées encore, ou celles qui gagneraient à être soumises à une nouvelle analyse à la lumière des connaissances récemment acquises. Enfin, il formule des recommendations concernant les travaux de recherche à venir.

TABLE OF CONTENTS

SUMMARY.....v
TABLE OF CONTENTS.....ix
LIST OF FIGURES.....x
LIST OF TABLES.....xi

1. INTRODUCTION.....1

2. STRUCTURAL LOADS AND RESPONSES OF HULLS AND APPENDAGES.....2
   2.1 Ice Induced Vibrations.....2
      2.1.1 Objectives.....2
      2.1.2 Data Obtained.....2
      2.1.3 Determination of Natural Vibration Frequencies.....4
      2.1.4 Hull-Ice Interactions.....6
      2.1.5 Shaft Response.....8
      2.1.6 Conclusions from the Structural Response Report.....9
   2.2 Ship Structures, Ice Loads and Pressures.....11
      2.2.1 Objective.....11
      2.2.2 Data Obtained.....11
      2.2.3 Finite Element Model.....15
      2.2.4 Results.....16
      2.2.5 Data Analysis.....20
      2.2.6 Conclusions from Ice Load Reports, Arctic Trials....22
      2.2.7 Conclusions from Ice Load Reports, Antarctic Trials.23
   2.3 Rudder and Steering Gear Loads.....24
      2.3.1 Objective.....24
      2.3.2 Program Overview.....24
      2.3.3 Measured Parameters.....24
      2.3.4 Trials Results and Analysis.....27
      2.3.5 Design Guidelines on Rudder Stock Sizing and Optimum Rudder Configuration.....34
      2.3.6 Conclusions from the Steering Loads Report.....37

3. MANOEUVRING PERFORMANCE.....38
   3.1 Objectives.....38
   3.2 Ice Cover.....38
   3.3 Measured Parameters.....38
   3.4 Conduct of Manoeuvring Tests.....40
   3.5 Analysis of Manoeuvring Data.....40
   3.6 Conclusions.....47

4. IDENTIFICATION OF DATA FOR FURTHER ANALYSIS.....48
   4.1 Introduction.....48
   4.2 Ice Induced Vibrations.....48
      4.2.1 Introduction.....48
      4.2.2 Hull Strain Gauge Measurements.....48
      4.2.3 Shaft Measurements.....49
   4.3 Ice Loads and Pressures.....51
   4.4 Rudder and Steering Gear Loads.....58
   4.5 Manoeuvring Performance.....58
   4.6 Video Records.....58
   4.7 Conclusions and Recommendations for Further Analysis.....59

5. REFERENCES.....60

APPENDIX A - INDEX OF POLAR CLASS REPORTS AND SOURCES OF DATA

LIST OF FIGURES

2.1 APPROXIMATE TRANSDUCER LOCATIONS.....3
2.2 STRAIN GAUGE LOCATIONS FOR INSTRUMENTED BOW PANEL.....12
2.3 OPERATING AREAS FOR ICE IMPACT LOADS (ARCTIC).....13
2.4 SINGLE FRAME FINITE ELEMENT MODEL OF CANT FRAME 41.....15
2.5 NUMBER OF EVENTS RECORDED VS HIGHEST AVERAGE PRESSURE....17
2.6 SIZE OF CONTACT AREA VERSUS ICE TYPE.....17
2.7 COMPARISON OF EXTREME ENVELOPE PRESSURE AREA CURVE WITH THOSE OBTAINED IN THE ARCTIC.....18
2.8 COMPARISON OF PEAK ENVELOPE PRESSURE VERSUS GIRTH ALONG THE FRAME WITH DATA COLLECTED IN THE ARCTIC.....19
2.9 COMPARISON OF PEAK ENVELOPE OF PRESSURE VERSUS LENGTH ALONG THE WATERLINE WITH DATA COLLECTED IN THE ARCTIC....19
2.10 COMPARISON OF MEASURED DATA WITH VARIOUS THEORIES.....21
2.11 CALCULATED PRESSURE-AREA CURVES FOR EQUAL PROBABILITY COMPUTED FOR LONG RETURN PERIODS.....21
2.12 INSTRUMENTATION BLOCK DIAGRAM.....25
2.13 RUDDER STOCK TORQUE PROBABILITY DISTRIBUTION.....29
2.14 PROBABILITY DISTRIBUTION OF RUDDER STOCK TORQUE AND HYDRAULIC PRESSURE IN STEERING GEAR.....30
2.15 TYPICAL IMPACT TIME HISTORIES.....31
2.16 STATIC STRUCTURAL MODEL OF POLAR STAR RUDDER FOR IN-PLANE BENDING.....33
2.17 NON-DIMENSIONAL REPRESENTATION OF RUDDER-ICE IMPACT TORQUES.....35
3.1 AVERAGE ICE THICKNESS FROM ICE EDGE TO HUT POINT.....39
3.2 USCGC POLAR STAR JANUARY 1985 MANOEUVRING TESTS.....42
3.3 USCGC POLAR STAR JANUARY 1985 MANOEUVRING TESTS.....43
3.4 VARATION OF R/L WITH ICE THICKNESS.....45
3.5 VARIATION OF R/L WITH CENTER SHAFT THRUST.....46
4.1 OUTPUT FROM DECK MOUNTED STRAIN GAUGES.....50
4.2 TIME HISTORY OF PROPELLER TORQUE AND THRUST DURING ICE INTERACTION - STARBOARD SHAFT.....52
4.3 TIME HISTORY OF PROPELLER TORQUE AND THRUST DURING ICE INTERACTION - CENTRE SHAFT.....53
4.4 TIME HISTORY OF PROPELLER TORQUE AND THRUST DURING ICE INTERACTION - PORT SHAFT.....54
4.5 TIME HISTORY OF PITCH DURING ICE INTERACTION - PORT, CENTRE, AND STARBOARD SHAFT.....56
4.6 MODE SHAPES AND FREQUENCIES FOR LONGITUDINAL VIBRATION OF PROPULSION SYSTEM - CENTRE SHAFT.....57

LIST OF TABLES

2.1	SENSORS FOR DATA RECORDING	3
2.2	NATURAL FREQUENCIES OF VIBRATION USCGC POLAR SEA	5
2.3	NATURAL FREQUENCIES OF HULL VIBRATION COMPARISON BETWEEN FULL EFFECTIVE AND FULL INEFFECTIVE SUPERSTRUCTURE	5
2.4	AVERAGE RMS FORCES FROM X AND Y ACCELEROMETERS	7
2.5	COMPARISON OF SHAFT FREQUENCIES WITH PROPELLER EXCITATION FREQUENCIES	8
2.6	SUMMARY OF ENVIRONMENTAL CONDITIONS	14
2.7	RANGE OF HYDRODYNAMIC LOADS	33
2.8	FREQUENCY OF IMPACTS FOR BACKING AND RAMMING	36
3.1	LOADING CONDITION OF USCGC POLAR STAR DURING	
3.2	REVIEW OF TEST DATA	41
4.1	SUMMARY OF SHAFT DATA DURING ICE/PROPELLER INTERACTION	55

1. INTRODUCTION

This report summarizes the accomplishments of four years of research onboard the USCG Polar Class Icebreakers sponsored by Transport Canada. The research programs represent Transport Canada's participation in a large scale program that has entered its ninth year, sponsored by a number of U.S. Government agencies and Commercial companies, principally U.S. Maritime Administration, U.S. Coast Guard, and the companies of the Arctic Oil and Gas Association.

This report was designed to convey the scope of the Canadian research program, present the extent and quality of the data, the principal achievements and results, catalogue the data and identify the sources, and highlight areas where further analysis of data may be of value. The research programs conducted under the sponsorship of U.S. agencies are not included herein, but will be the subject of a later report. However, the reports of the U.S. sponsored research are generally available in Transport Canada. The report covers work performed to January 1985.

The Transport Canada tests are discussed under three categories, for which the following brief description is given.

Ship Structure:

In 1981 [1] trials were performed in order to record the vibratory response of the USCGC POLAR SEA and to develop a model of the ice-breaking excitation forces.

In 1982 the bow of the POLAR SEA was instrumented to measure ice loads. This unique instrumentation system permitted the derivation of loads, pressures and areas of ice impact. Data was recorded in the Beaufort and Bering Seas in Summer 1982 and Winter 1983 [2]. The system was operated again in the Antarctic in 1984 [3], and further data collection took place in the Beaufort Sea in Summer 1984 [11].

Rudders and Steering Gear

The magnitudes and characteristics of loads imposed on steering systems as a result of ship/ice interactions were studied onboard the POLAR STAR in 1982 [4]. In addition, full scale data obtained from previous full scale ship trials was analyzed and compared.

Manoeuvring Performance

A full-scale test program to assess the manoeuvring performance of Polar Class vessels in level ice was carried out during the 1984/85 Antarctic summer [12]. The trials consisted of 19 turning tests carried out at constant power level with the rudder angle held constant. Two mathematical models were developed to predict turning circle diameters - one making use of a time-stepping approach which generates the turn trajectory and a second method involving a force balance method using an assumed hull-side force distribution. Analysis of the measured data and preliminary comparisons of the predicted and measured turning diameter have shown that further controlled tests at large rudder angles will be required for complete validation of the mathematical models.

2. STRUCTURAL LOADS AND RESPONSES OF HULLS AND APPENDAGES

2.1 Ice Induced Vibrations

2.1.1 Objectives

i) To measure the form and magnitude of hull vibrations onboard USCGC POLAR SEA during an icebreaking trials expedition near Point Barrow in January and February 1981.

ii) To record and store measured data in a readily accessible manner for future use as well as immediate review and analysis.

iii) To identify, characterize and develop a mathematical model for the icebreaking forces which excite hull vibrations.

2.1.2 Data Obtained

Calculations and data analysis were carried out to determine:

i) Natural frequencies of vibrations
ii) Hull/ice interactions - accelerations
- ice impact forces
iii) Open water (vibration) performance - turning
- crash reversals

To attain these objectives an instrumentation system consisting of accelerometers, strain gauges, and ancilliary recording equipment was installed as in Figure 2.1 and Table 2.1. In addition, closed circuit video equipment and a doppler radar were installed on the vessel.

The data obtained from this instrumentation was collected on 26 magnetic tapes and 16 video tapes. This data covers approximately 100 hours of testing: Annex 3 of report TP4080E (Winter 1981 Trafficability Tests) [1] contains the shipboard trials log describing the incidents and associated tape numbers and counts.

The frequencies at which the hull vibrated were determined using the acceleration spectrum and a Fast Fourier Transform analyser. This analysis was performed to measure the frequencies of peak acceleration magnitudes in the following ship-ice impact scenarios:

- open water turning
- crash reversal
- backing in level ice
- continuous ice transit
- ramming level ice
- ramming pressure ridges

FIGURE 2.1

APPROXIMATE TRANSDUCER LOCATIONS

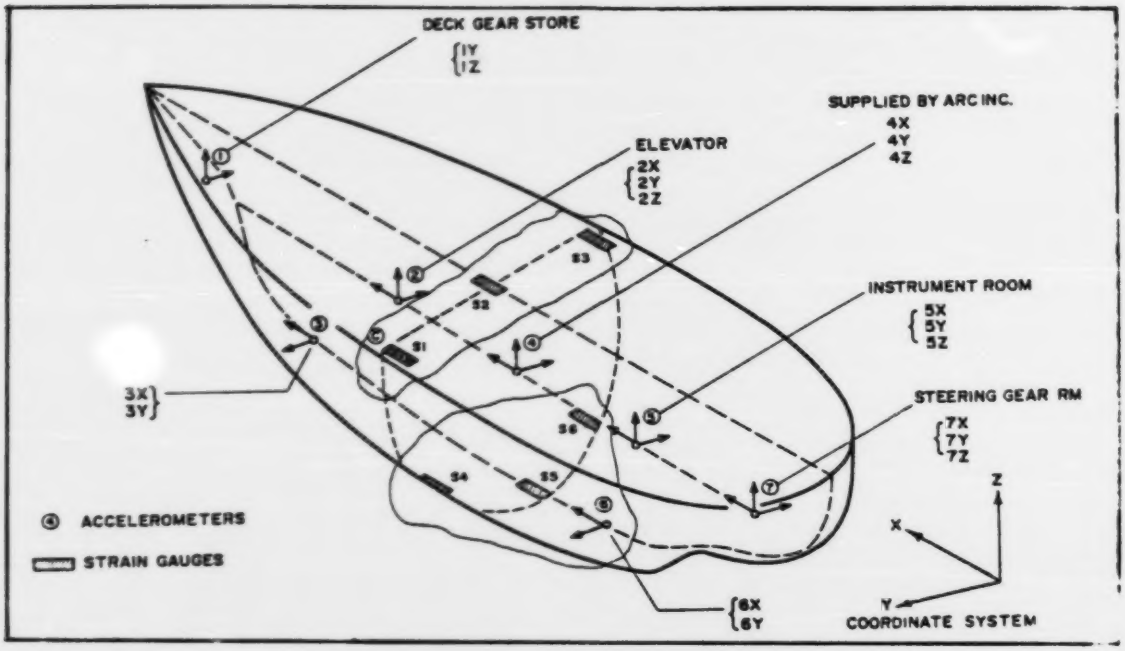


TABLE 2.1

SENSORS FOR DATA RECORDING

DESIGNATOR	TYPE	FUNCTION
S1	Strain Gauge	Longitudinal Bending
S2	"	"
S3	"	"
S4	"	"
S5	"	"
S6	"	"
1Y	Accelerometers	Bow Transverse Acceleration
1Z	"	Bow Vertical Acceleration
2X	"	Forward Upper Deck Longitudinal Accel.
2Y	"	Forward Upper Deck Transverse Accel.
2Z	"	Forward Upper Deck Vertical Accel.
3X	"	Forward Machinery Compartment Long.
3Y	"	Forward Machinery Compartment Transverse
4X	"	Ships Centre of Gravity Long. Accel.
4Y	"	Ships Centre of Gravity Transverse Accel.
4Z	"	Ships Centre of Gravity Vertical Accel.
5X	"	Upper After Deck Longitudinal Accel.
5Y	"	Upper After Deck Transverse Accel.
5Z	"	Upper After Deck Vertical Accel.
6X	"	After Machinery Compartment Longitudinal Accel.
6Y	"	After Machinery Compartment Transverse Accel.
7X	"	Stern Longitudinal Acceleration
7Y	"	Stern Transverse Acceleration
7Z	"	Stern Vertical Acceleration

2.1.3 Determination of Natural Vibration Frequencies

The first few natural frequencies of the hull vibration in the vertical and horizontal directions were calculated using the David W. Taylor Naval Ship Research and Development Centre's Generalized Bending Response Program (GBRP). The ship's hull was represented by a non-uniform continuous free-free beam with mass and elastic properties per unit length being equivalent to those of the actual ship.

Mode shapes and frequencies were calculated up to the fifth flexural mode for vertical and horizontal vibration and up to the sixth flexural mode for longitudinal vibration. Hull and structural parameters for input into this program can be found in Annex 1 of the report [1]; examples of GBRP output and sample calculations are contained in Annex 2. Table 2.2 gives the calculated frequencies of vibration. The natural longitudinal frequencies of vibration for the centre and wing shafts were also calculated up to the third mode using the GBRP.

The frequencies given by GBRP assumed the superstructure was totally ineffective and made no contribution to hull stiffness. A comparison was also made to show the contribution of a fully effective superstructure, and the results are shown in Table 2.3. The effect of the superstructure was more pronounced for vertical vibration and at higher frequencies.

Frequencies of vibration were measured in the ship structure by using a power spectral density function from a frequency spectrum analysis of accelerations.

Relatively large responses were measured at the centreline shaft rotational frequency of 2.875 Hz and the propeller blade frequency of 11.375 Hz. These frequencies are close to the 2 node vertical frequency of 2.74 Hz, the 6 node vertical frequency of 11.52 Hz and the 4 node horizontal frequency of 10.87 Hz calculated by the GBRP; therefore this large response suggests this program correctly calculated natural frequencies.

An additional verification of these frequencies was made by comparing the predictions of Schlick's empirical formula [5]. This formula predicts a 2 node frequency of 2.84 Hz, less than 2% different from that given by the GBRP.

TABLE 2.2

NATURAL FREQUENCIES OF VIBRATION
USCGC POLAR SEA

Assumed Displacement = 12192 long tons
Superstructure - all structures above 01 deck assumed ineffective

MODE DESCRIPTION / MODES / NODES	FREQUENCY (Hz)							
	LATERAL	ROTATIONAL	FLEXURAL					
	0	1	1	2	3	4	5	6
Vertical - Hull	.1618	.186	2.74	5.00	7.26	9.46	11.52	
Horizontal - Hull	-	-	4.13	7.43	10.87	14.47	17.44	
Longitudinal - Hull	-	8.41	16.11	22.6	28.60	35.82	42.07	47.82
Longitudinal - Center Shaft	9.48	24.03	49.02	106.59				
Longitudinal - Wing Shaft	9.43	24.88	53.79	111.74				

TABLE 2.3

NATURAL FREQUENCIES OF HULL VIBRATION
COMPARISON BETWEEN FULL EFFECTIVE AND FULL INEFFECTIVE SUPERSTRUCTURE

MODE/NODE	2	3	4	
SUPERSTRUCTURE INEFFECTIVE		FREQUENCY (cycles/sec)		SUPERSTRUCTURE FULLY EFFECTIVE
VERTICAL	2.74	5.00	7.26	
	3.47	6.83	10.18	VERTICAL
HORIZONTAL	4.13	7.43	10.87	
	4.33	8.83	13.73	HORIZONTAL

2.1.4 Hull-Ice Interactions

During ice ramming the results indicated that ramming induced rigid body accelerations at frequencies below 0.5 Hz, and flexural vibration accelerations occurred at frequencies of up to about 3 Hz. Vertical hull vibration at its fundamental frequency (about 2.74 Hz) was noticeable during ice ramming operations.

During level ice transit, cusp breaking of the ice at the bow was shown to account for frequencies in the 0.5 - 1.5 Hz band, found in the horizontal accelerations. In all scenarios hull vibration at shaft and propeller blade frequencies were found at all accelerometers.

In open water operations, the level of vibration at the stern was usually an order of magnitude higher than that at the bow. In ice-transiting operation the opposite trend was evident, particularily in ramming incidents.

Root mean square (RMS) ice impact forces were calculated from computed force spectra derived from the measured acceleration spectra for eight selected ramming cases (from an original data base of 19 incidents) where there was:

a) evidence of a clear sharp impact
b) confident estimation of pre-impact conditions
c) clear visual evidence of heave, surge and sway

Examination of the computed force spectra indicated that the spectra had one to four peaks in the frequency range from 0.125 Hz to 2 Hz as well as a series of peaks around 10 - 12 Hz. In the frequency range below 2 Hz the peaks could be related to ice interactions; the series of peaks between 0.5 and 1.5 Hz occurred at cusp breaking frequencies and logically could be accounted for by this phenomenon. The spike at 0.125 Hz could result from ice crushing during the initial contact.

The RMS ice forces occurring at the bow were calculated from the accelerometer responses during the eight ramming incidents. This was done using a modal analysis assuming the ship to be a linear elastic structure with known mass and stiffness distribution, computed natural frequences and mode shapes, assumed structural damping factor and assumed distribution of the external force. These forces were calculated as RMS forces during each incident and should not be confused with the peak force which would occur within the eight second recording period of the impact. The average of the RMS forces from X and Y accelerometers for each incident are presented in Table 2.4.

TABLE 2.4

AVERAGE RMS FORCES FROM X AND Y ACCELEROMETERS

ACTIVITY (ICE THICKNESS)	IMPACT POSITION	TEST	RMS VERTICAL FORCE (Tons)	RMS HORIZONTAL FORCE (Tons)
Ramming Level Ice/P.R. (Maximum 4')	Oblique (6 kn)	F8 0	48.59	34.53
Ramming Level Ice (Maximum 4')	Oblique (9 kn)	F8-1	104.82	220.56
Transit Ramming (Maximum 2')	Oblique	F8-2	59.68	93.13
Ramming Level Ice (Maximum 4')	Head-on (5.33 kn)	F9-0	48.12	61.09
Transit Ramming (Maximum 4')	Head-on (9 kn)	F9-1	64.88	108.07
Transit Ramming	Oblique (7 kn)	F9-2	87.27	149.73
Transit Ramming (Maximum 3')	Head-on (12 kn)	F9-4	65.15	115.57
Ramming Level Ice (Maximum 3')	Head-on (4 kn)	F9-5	58.13	48.01

Root Mean Square Ice Forces at Bow of USCGC POLAR SEA, Derived From Measured Accelerations.

2.1.5 Shaft Response

In order to correctly model the transmission of propeller induced loading into the hull, and to study the relationship between shaft dynamic response and loadings, a structural dynamic analysis of the shafting was performed for the shaft longitudinal direction only. The propeller and shaft (for wing and centre shafts) were modelled as a series of concentrated masses and elastic elements, and the stiffnesses of thrust bearing foundations, thrust bearing were calculated. Hydrodynamic inertias were included in the calculation.

Mode shapes and frequencies for the shaft were calculated for both the actual and infinitely stiff bearing foundations and the variation of shaft natural frequencies with stiffness were calculated. This showed that, in the event that it is desired to change the frequency of the shaft system (for example, because of interference with blade rate excitations), changing the stiffness of the shaft bearing foundation was not very effective.

The calculation showed that the lowest longitudinal frequencies of the shaft were very close to the blade rate frequencies and that some form of dynamic amplification of loads transmitted to the hull would be likely. Shaft and blade rate frequencies were evident in the measured hull response (Table 2.5).

The model was developed for longitudinal response only, but as discussed in Section 4, the potential for deriving propeller loads from total shaft response via a suitable model exists, if the measured shaft data is examined.

TABLE 2.5

COMPARISON OF SHAFT FREQUENCIES WITH PROPELLER EXCITATION FREQUENCIES

SHAFT	SHAFT SPEED (rpm)	f_e PROPELLER EXCITATION FREQUENCY, Hz (BLADE FREQ.)	f_n LOWEST LONGITUDINAL FREQUENCY, Hz	f_e/f_n ./.
WING	110	7.32	9.43	78
CENTERLINE	130	8.68	9.48	92

2.1.6 Conclusions from the Structural Response Report (1981)

These conclusions are reproduced for the original report and may not have supporting analysis reported herein.

1. The natural frequencies of the hull of the USCGC POLAR SEA were calculated using the GBRP [5]. This program does not use finite element theory but idealizes the ship as a non-uniform free-free beam with equivalent mass, elastic and inertial properties. Comparing these calculations with empirical formulae [6] indicated agreement within 2% for the vertical mode and 20% for the athwartship mode.

2. The longitudinal natural vibration frequencies for wing and centre shafts were calculated by the same method. For all shafts the fundamental longitudinal frequencies were found to be near propeller blade frequencies at normal RPM. The wing shaft frequency was 22% above the blade frequency of 7.32 Hz at 110 RPM while the centre line shaft frequency was only 8% above the blade frequency of 8.68 Hz at 130 RPM. This confirms the possibility of dynamic amplications of thrust vibrations.

3. A study of the acceleration profiles generated from full scale vibration data for ship-ice interaction incidents, indicated that the vibrations of the hull structure were predominantly a combination of rigid body modes and the first flexural mode (i.e.2 nodes).

4. Acceleration spectra produced for open water turning and crash reversal, continuous ice transit, backing and ramming, etc. indicated that:

   - Impact with ice (e.g. during ramming) induced rigid body accelerations at frequencies below 0.5 Hz and flexural vibration accelerations up to about 3.0 Hz.

   - During icebreaking (e.g. continuous transit) side-cusp encounter frequencies induced vibrations in the 0.5 to 2.0 Hz frequency range, the athwartship component being larger than the vertical and more pronounced at the bow than at the stern.

   - Hull vibrations at various propeller blade and shaft frequencies were evident, particularly at the after end of the ship.

   - In open water, the level of vibration at the stern has been found to be an order of magnitude higher than at the bow, while in the ice-transiting mode the opposite occurs.

   - When icebreaking bow accelerations increased by an order of magnitude while a decrease occurred at the stern.

   - Cases of the ship's hull responding in its mode-forms of vibration are also evident.

5. RMS bow impact forces were calculated for eight cases from the acceleration spectra using a transfer function developed from the structural response model. The results from all accelerometers were in agreement for four cases. The major limitation of this model was that the external force location had to be known.

6. Strain gauge data from both the hull and the shafting was not analyzed.

2.2 Ship Structures, Ice Loads and Pressures

2.2.1 Objective

The objective of the 1983-84 programs was to collect ice loads on an instrumented panel on the port bow of the USCGC POLAR SEA. Force, impact area and pressure were measured during impacts in a variety of ice conditions. This program was sponsored by Transport Canada and the U.S. Agency Ship Structures Committee and is reported on fully in Transport Canada reports [2] and [3].

2.2.2 Data Obtained

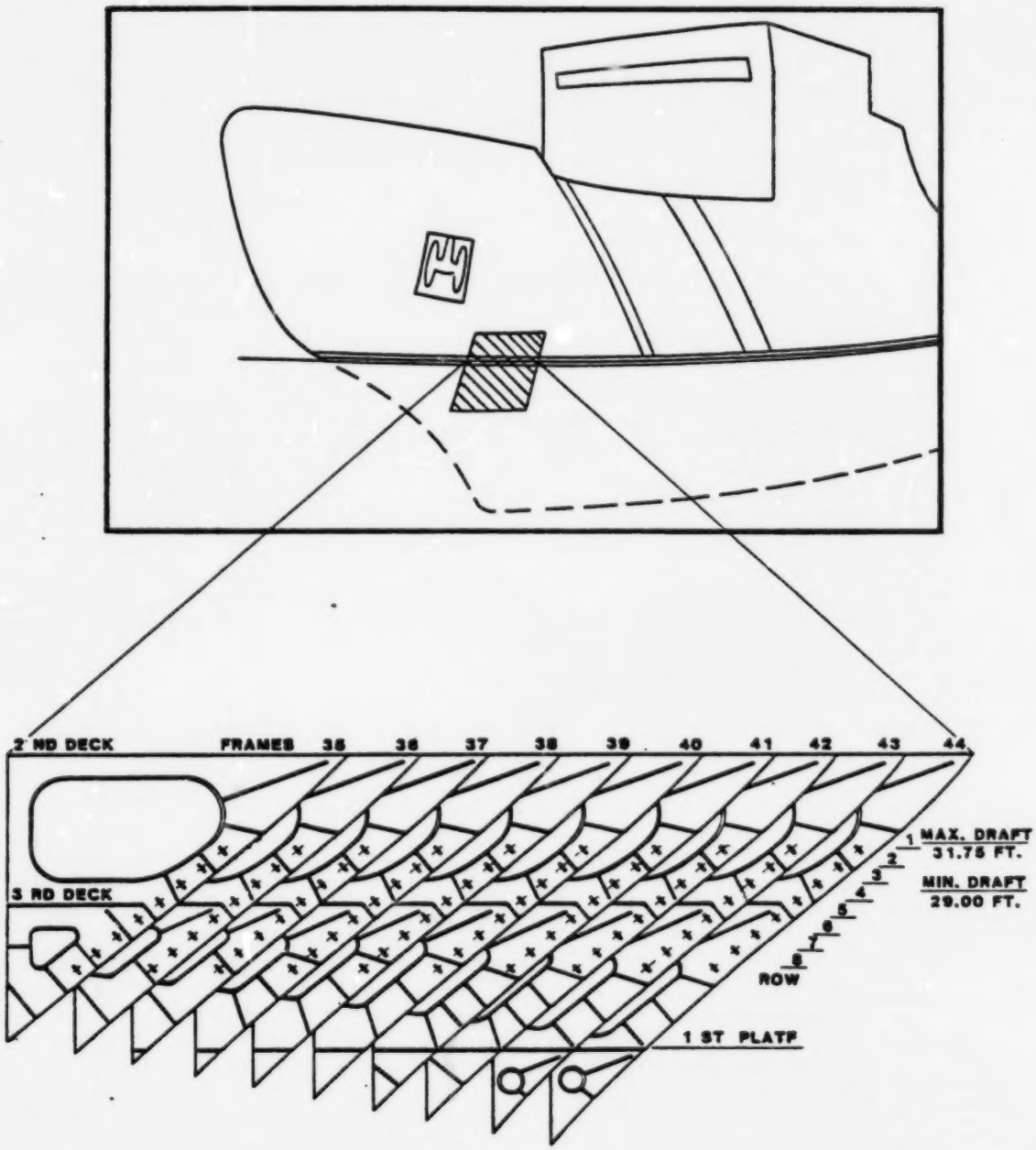
A portion of the bow, chosen such that there was a high probability of experiencing peak loads, was instrumented to obtain the loading data. The measurement system measured the compression in the web of the cant frames, a novel technique selected after a finite element analysis of the frames. This system permitted each compression gauge to be located so that it only sensed loads in the portions of the hull immediately adjacent to the gauge. This resulted in a data reduction matrix that uniquely specified the position and magnitude of the load for each set of strain gauge readings.

The gauges were evenly spaced vertically along the frames and horizontally on successive frames to form a panel of regular subpanels, 380 mm high x 410 mm wide. Eighty subpanels were formed in eight rows of ten as shown by Figure 2.2. Six rows were active at one time, switchable to acommodate changes of draft.

The data acquisition system was designed to accommodate the large volume of data and the requirement for real-time onboard data presentation. Based on a microprocessor, the system scanned 60 channels at 32 Hz. If any channel exceeded a preset threshold strain all channels were recorded for five seconds on a digital tape recorder. One second of this data was prior to threshold exceedance, held by a buffer.

In the September-October 1982 (Summer) deployment of POLAR SEA north of and between Point Barrow and Prudhoe, Alaska, at and above 72°N, the system was checked out and 167 good impacts were recording during some fifty hours of operation over a two week period in multi-year ice. Data was collected during dedicated rams of the multi-year floes or while in transit. The three modes were: transiting at slow to moderate speed in open water and impacting floes; backing and ramming in heavy multi-year ice; and slow continuous progress in multi-year ice.

Data was collected in the winter deployment over 41 days between March and May 1983 in the Bering and South and North Chukchi Seas, with the principal trials being conducted off Wainwright, Alaska in ice. In this second deployment 1226 events were recorded, 67 in multi-year ice, 61 in dedicated tests with well documented ice conditions. Figure 2.3 shows the geographic location where the Arctic tests were conducted.



STRAIN GAUGE LOCATIONS for INSTRUMENTED BOW PANEL ABOARD the POLAR SEA

FIGURE 2.2

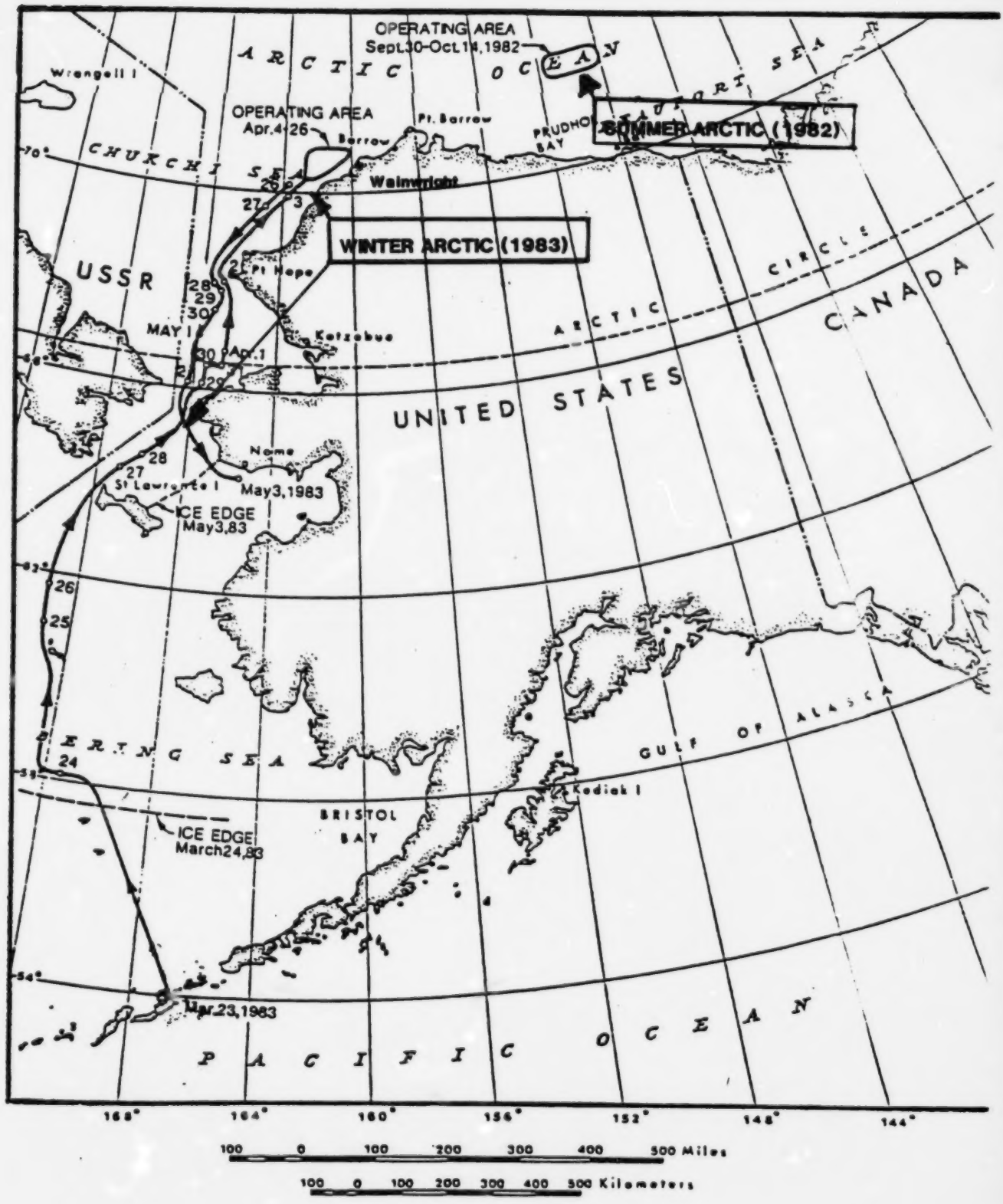


Figure 2.3

OPERATING AREAS FOR ICE IMPACT LOADS (ARCTIC)

Between January 9 and January 13, 1984 data was collected in McMurdo Sound, Antarctica during an operation to resupply McMurdo Station by sea. Ice thickness varied from 0.9 to 1.8 m and 309 events were recorded. This data was recorded while the icebreaker was widening the channel, therefore the data is assumed to result mostly from single side impacts.

Approximately 10,000 individual pressures are computed for each event. Reduced data included 60 channel pressure time history, a summary of the pressure versus area curve, total panel force time history, directory and comments on observed ice conditions and speed. Additionally in the second deployment the time of peak force was determined.

TABLE 2.6

SUMMARY OF ENVIRONMENTAL CONDITIONS

VARIABLE	DEPLOYMENT WINTER 1981 (ARCTIC)	WINTER 1982 (ARCTIC)	SUMMER 1984 (ANTARCTIC)
Daily Average Air Temperature °C			
- maximum	- 10.1	2.8	1.7
- minimum	- 53.9	- 18.3	- 7.4
Hourly Windspeed (m/s)			
- maximum	20.6	14.9	8.7
- minimum	4.1	2.6	0
Level Ice Thickness (m)			
- first year maximum	1.2	1.0	1.8
- first year average	0.8 - 1.2	0.6 - 0.7	1.5
- multi-year maximum	5.5	-	-
- multi-year average	1.5 - 5.5	-	-
Ridged Ice Thickness (m)			
- sail maximum	FY 1.6 - MY 15.5	3.6	-
- sail average	MY 6 - 12	1.8	-
- keel maximum	FY 4.0 - MY 15.5	12.3	-
- keel average	-	2.7 - 6.6	-
Calculated Flexural Strength (kPa)			
- first year ridge	-	413	-
- first year level (avg.)	428	171	182 - 316
- multi-year level (avg.)	816	-	-

- indicates none measured during deployment

2.2.3 Finite Element Model

A finite element model of the structure was prepared, both to locate gauges and to provide a 'stiffness' matrix to convert strains to loads and pressures. The type of structure was such that it was sufficient to model only one frame (at centre panel) in detail, while a second, multi-frame model of all frames was developed to assess the transfer of loads through the plating to the frames. The assumption inherent in this approach was that all frames were similar. Figure 2.4 depicts a frame finite element model.

Exercising the model under point loads at each gauge location it was determined that with gauges 373 mm (14.7") apart along the frame and 230 mm (9") from the shell, the loading effect was localized to a point so that load at one gauge caused near zero strain at the adjacent gauge along the frame. Thus a near diagonal stiffness matrix resulted making the algorithms simpler. Using the multi-frame model, the longitudinal or across frame influence was found. In this case, if the gauge under the load was assumed to have 100% strain, that on gauges at the same level (row) on immediately adjacent frames was 10% and 0.1% at the next closest frame.

The conversion of strains to ice impact pressures was achieved through the data reduction matrix assuming the ice load on the panel was approximated by a distinct group of mutually independent pressures acting over the 380 x 410 mm area influencing each gauge.

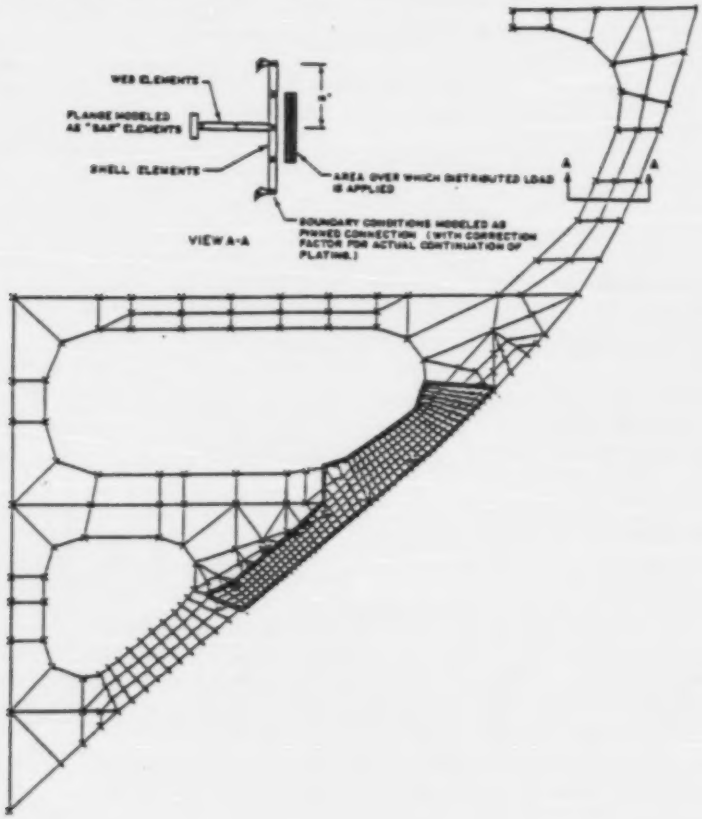

WEB ELEMENTS
FLANGE MODELED AS "BAR" ELEMENTS
SHELL ELEMENTS
AREA OVER WHICH DISTRIBUTED LOAD IS APPLIED
BOUNDARY CONDITIONS MODELED AS PINNED CONNECTION (WITH CORRECTION FACTOR FOR ACTUAL CONTINUATION OF PLATING)
VIEW A-A
A
A

FIGURE 2.4

SINGLE FRAME FINITE ELEMENT MODEL OF CANT FRAME 41

2.2.4 Results

Arctic Summer:

The emphasis throughout the data reduction and analysis was on peak pressures as it is this parameter that has the most significance to the designer. The distribution of highest average pressures, Figure 2.5, showed that 75% of the event data had an impact area of 0.91 m^2 or more while 5% of the data had an impact area of at least 4.7 m^2. The highest single panel pressure recorded was 11.15 MPa, which occurred while backing and ramming in multi-year floes. The highest single panel pressures appeared randomly located, but there were a large number of impacts low on the panel in thick ice. Forty eight percent of the impacts peaked in the lower two rows of the panel.

Arctic Winter:

The highest average pressure statistics were plotted, as in the summer results, for combinations of subpanels. Data was grouped according to geographical area.

Examination of the location where impacts were most frequent, showed the majority centered around frame 43 at the aft end of the panel with most events occurring vertically within but towards the bottom of the panel.

Comparison of the extreme pressure area envelopes for geographical areas showed increased pressure with increased severity of ice as the ship moved North. The north Chukchi Sea multi-year ice data has substantially higher pressures. Increasing peak force with velocity was found from dedicated ramming of multi-year ice. Relationships between peak force and pressure with thickness and velocity from the first year ice data showed little trends with peaking at intermediate thicknesses.

Antarctic:

Impact frequency versus highest average pressure was tabulated and showed unexpectedly large contact areas; 18% of the impacts covered areas of at least 4.7 m^2. A comparison of this data with that recorded in the Arctic is shown in Figure 2.6, which shows more occurrances at smaller areas in the Antarctic than measured in the Arctic. Peak pressure and force were compared with impact velocity and a trend of increasing peak force with speed was indicated.

Highest average pressures were found to be linearly related to area, for areas of less than 2.8 m^2 and to follow a constant force relationship for larger areas. In Figure 2.7 the data is compared for Arctic and Antarctic trials and lower pressures are shown for the Antarctic at areas below 2.8 m^2. At larger areas equivalent pressures were encountered. An explanation for these lower pressures is that the higher pressures are due to confinement occuring during ridge failure by crushing. No ridges were encountered in McMurdo Sound. Curves which may be of interest to designers are presented in Figures 2.8 and 2.9 which present these pressure-area relationships as a function of stringer or frame span. The same trends as discussed earlier are shown.

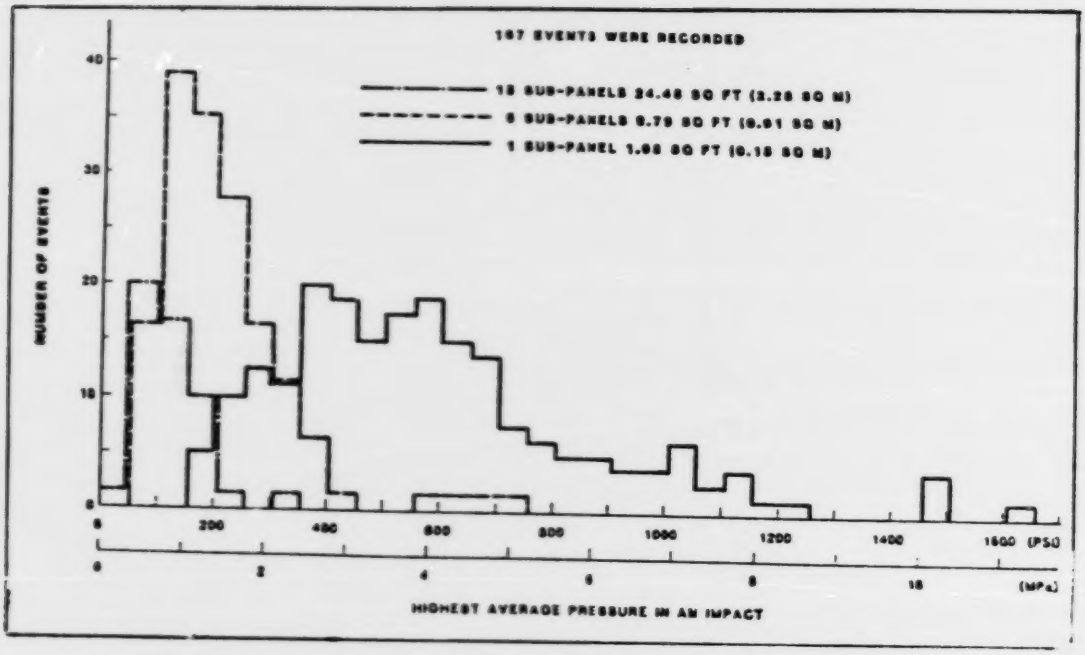


FIGURE 2.5

NUMBER OF EVENTS RECORDED vs HIGHEST AVERAGE PRESSURE FOR DIFFERENT IMPACT AREAS (BEAUFORT SEA, SUMMER)

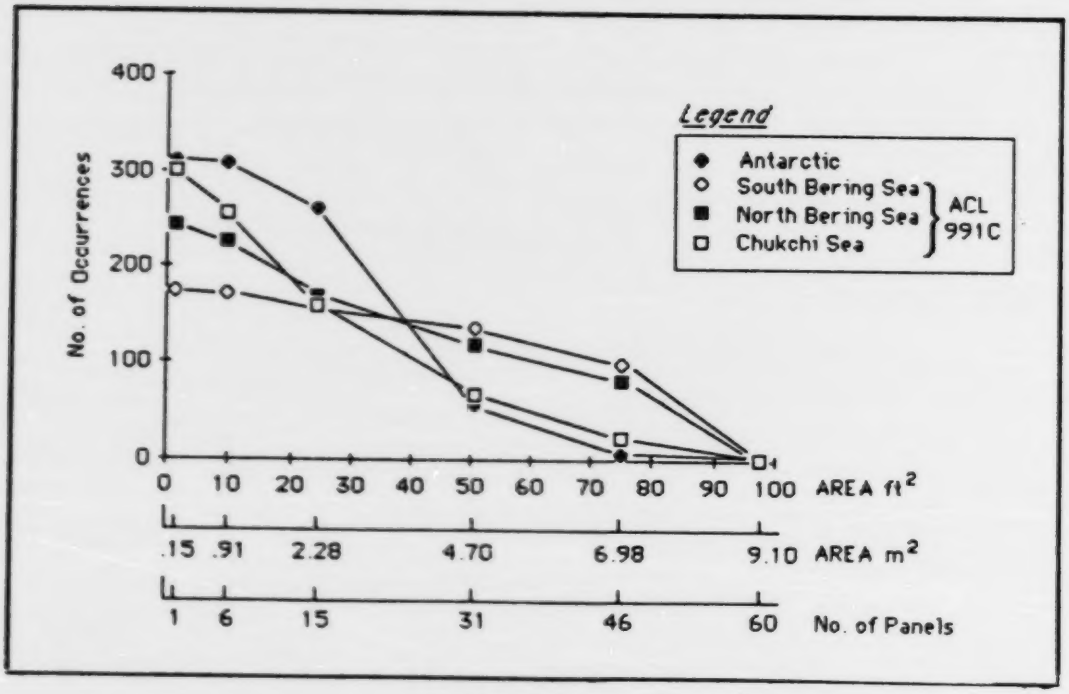


FIGURE 2.6

SIZE OF CONTACT AREA VERSUS ICE TYPE

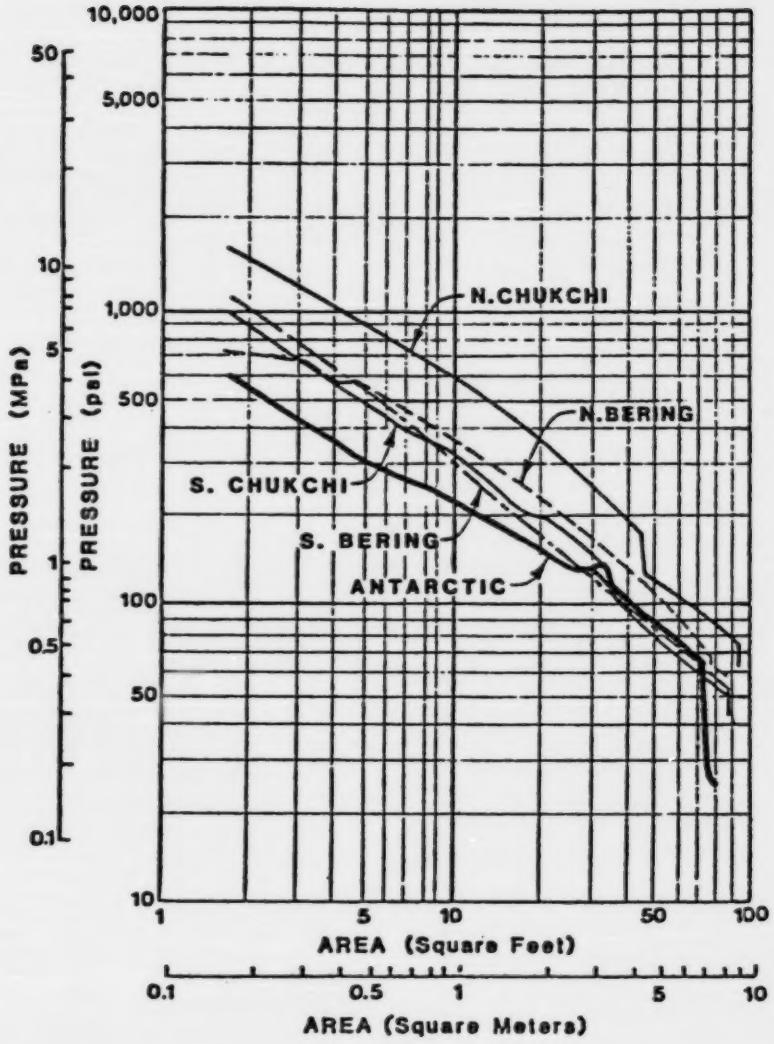


Figure 2.7

COMPARISON OF EXTREME ENVELOPE PRESSURE-AREA CURVE WITH THOSE OBTAINED IN THE ARCTIC

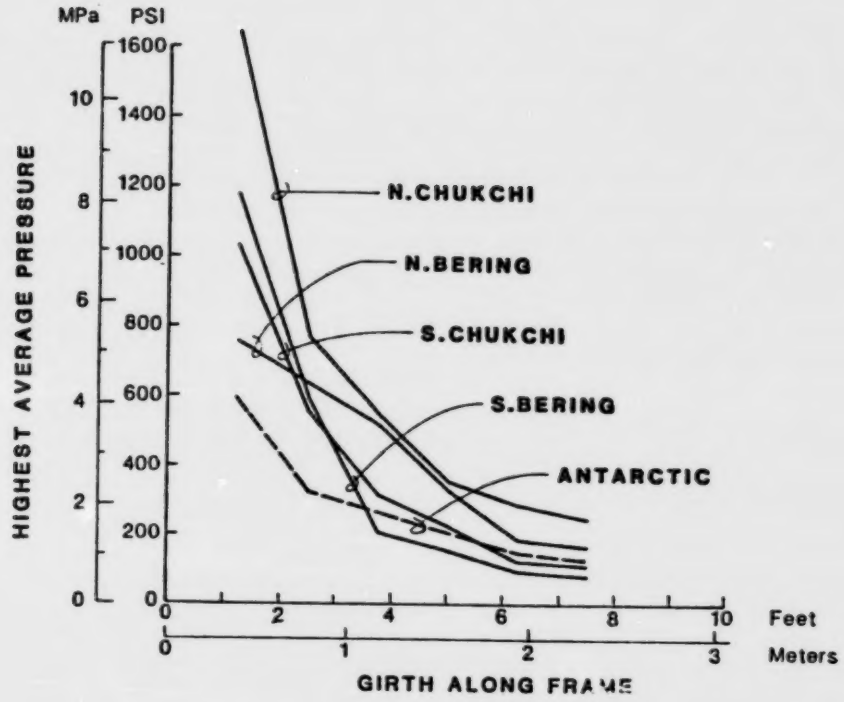


Figure 2.8

COMPARISON OF PEAK ENVELOPE OF PRESSURE vs. GIRTH ALONG THE FRAME WITH DATA COLLECTED IN THE ARCTIC

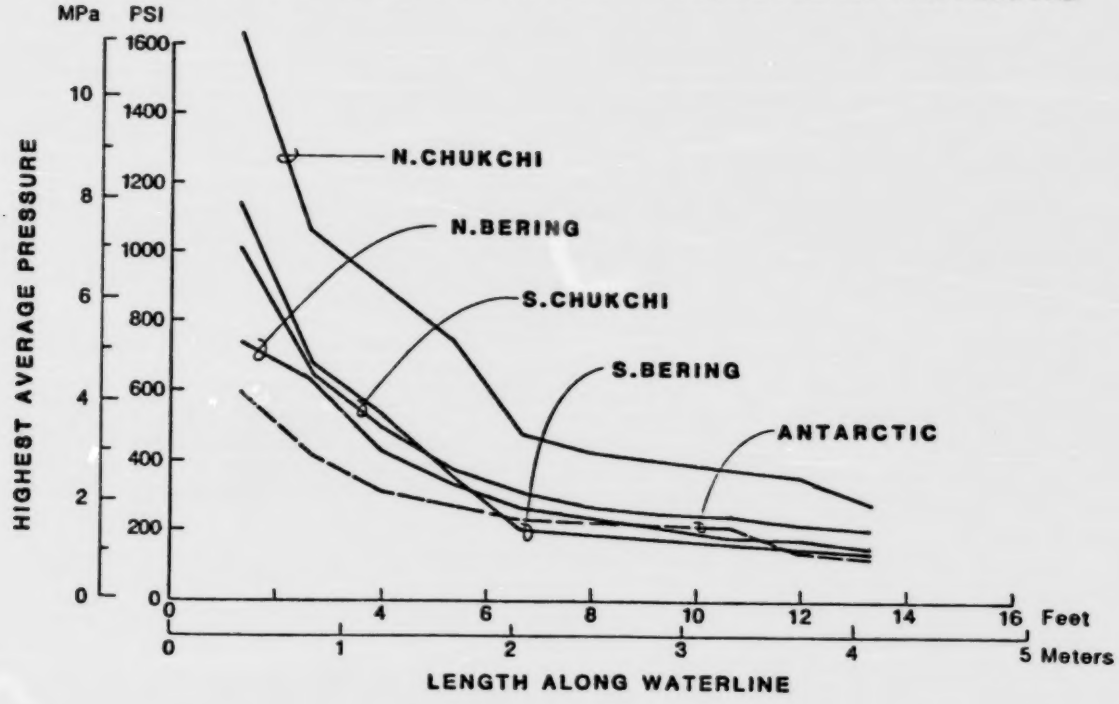


Figure 2.9

COMPARISON OF PEAK ENVELOPE OF PRESSURE vs. LENGTH ALONG THE WATERLINE WITH DATA COLLECTED IN THE ARCTIC

2.2.5 Data Analysis

The measured data were compared with Nevel's theory [7] which predicts the vertical force required to first crack an ice sheet; and Kerr's theory [8] for the total static load an ice sheet can support. The bands of forces for these theories for ice thicknesses between 0.9 and 1.8 m are shown in Figure 2.10 together with the curves of dynamic force predicted by a simple formulation developed by Daley [9]. Whereas the measured data clearly does not fit the static formulations, the dynamic force curves bound nearly all the data thus confirming the importance of considering the phenomenon as dynamic.

The variation of pressure and contact area with time was investigated and some confinement effects were observed.

Statistical Analysis:

A selected portion of the Arctic winter data was subjected to an extreme value analysis to estimate the expected maximum ice pressures. The selection was based on relatively constant environmental parameters, and the quality of measured variables. This data was plotted on Gumbel Type 1 and Type 2 probability axes, and the data for single subpanels fit a Type 2 distribution while the larger panels were better represented by a Type 1 distribution. Use of the correct distribution is important as the extreme pressures predicted over ten years varied from 20 MPa with a Type I distribution to 49 MPa with a Type 2 distribution.

The Antarctic data were plotted using Gumbel and log-extreme value distributions. The Gumbel distribution, appeared to be a better fit, although the amount of data (309 points), was small for evaluating an extreme value distribution.

Design Pressure - Area Relationship:

A plot of pressure and area for the data subjected to statistical analysis was made at a single 'probability' of occurrance value, using the equation:

$$P(A) = C_1 + 0.5 - \left(\frac{\ln\left(-\ln^{(F_p(P))}\right)}{C_2 A + 0.35}\right)$$

where P is the ice pressure, A the impact area and $F_p(P)$ is the probability of not exceeding P. These equations are shown in Figure 2.11, and can be used to design for a given life cycle. This equation can not be used confidently for other vessels and conditions; however, as a large data base must first be developed for a full range of ships.

Comparison with Previous Data:

Force data measured in this study was compared in a nondimensional manner with other published data.

The forces and pressures measured in this series are compatible with other published data. They agree at smaller areas with current CASPPR and Soviet Rules, although design pressures might be expected to be above those measured.

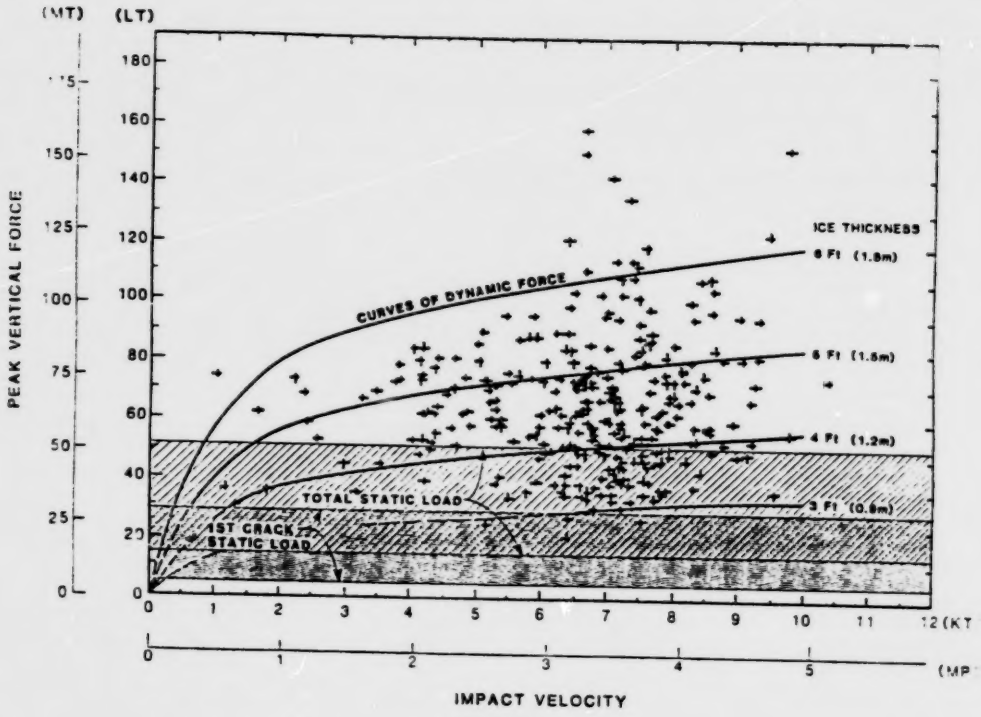


FIGURE 2.10

COMPARISON OF MEASURED DATA WITH VARIOUS THEORIES

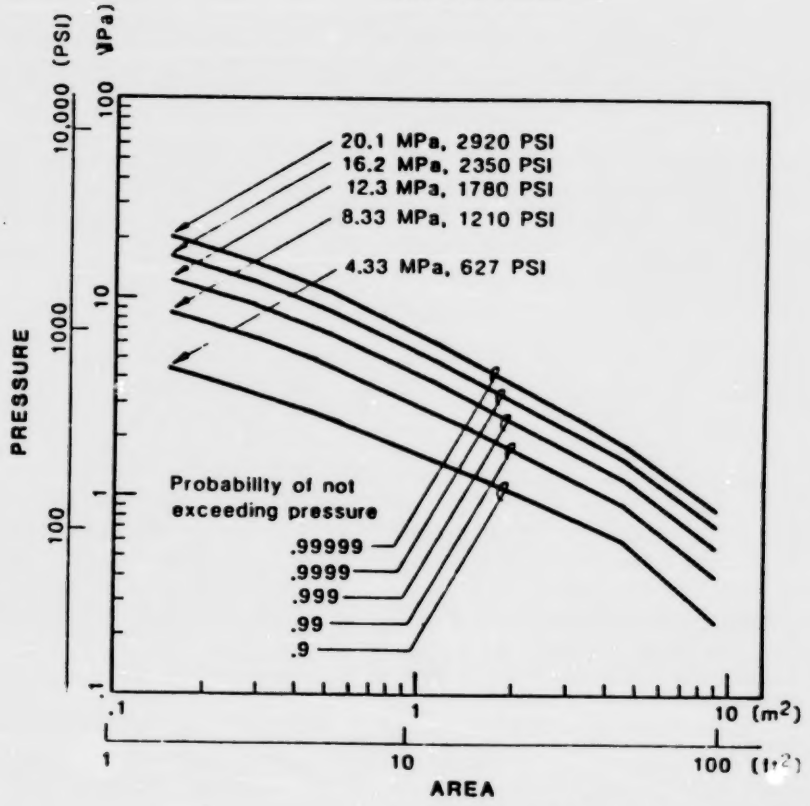


FIGURE 2.11

CALCULATED PRESSURE-AREA CURVES FOR EQUAL PROBABILITY COMPUTED FOR LONG RETURN PERIODS

2.2.6 Conclusions from Ice Load Reports (1983, 1984) Arctic Trials [2]

These conclusions are reproduced from the original report and may not have supporting analysis reported herein.

1. The technique measuring compression in the frame webs over a regular 'grid' of approximately 380 mm x 410 mm (15" x 16") panels and a total area of approximately 9 m^2 (100 ft^2) was most successful and resulted in accuracies of pressure measurement of +10%.

2. The internal calibration system used to verify the Finite Element model of the structure worked well for normally loaded cases.

3. Impacts were randomly distributed over the frames but were grouped in the lower area of the panel in multi-year ice.

4. The highest pressures were recorded in dedicated rams in multi-year ice and, specifically, while ramming summer multi-year floes.

5. Ice forces for transiting data increased with increasing ice thickness to a maximum observed ice thickness of about 4 to 6 feet (1.2 to 1.8 m) and then decreased at thicker ice conditions possibly due to voluntary speed reduction in perceived more severe ice.

6. Peak pressures appear relatively independent of speed and ice thickness and no significant trend with ship size based on comparison of this and other measured data is seen.

7. Peak pressures on a single sub-panel were approximately 2 times the unconstrained crushing strength calculated from temperature and salinity measurements.

8. The average pressure can increase with impact area indicating confinement effects.

9. Peak pressures measured over small areas in the test period reached levels similar to those currently promulgated as design pressures in the Rules.

10. Statistical analysis of the extremes of average pressure over different areas indicated that small area pressures are best represented by a Type II (log-normal) probability distribution and large areas are best represented by a Type I (Gumbel) probability distribution. The Type I distribution can be used to approximate the extremes of average pressure over all areas and extrapolate the pressure-area curve to longer return periods with good agreement.

11. An approach to the development of design pressure-area relationships based on ice conditions and ship parameters has been developed which shows promise and provides a focus for the objectives of future test programs.

2.2.7 Conclusions from Ice Load Reports - Antarctic Trials [3]

1. The envelope of the data showed single sub-panel pressures (areas of 1.6 ft or .15 m) of less than 600 psi (4.1 MPa) and total panel forces less than 270 LT (265 MT). These pressures and forces are less by a factor of 2 to 3 than those recorded in the Arctic.

2. Speed effects were not apparent in the single sub-panel pressure or total force data, however, see 3 below.

3. There appears to be good agreement between the vertical force prediction equation proposed by Daley [9], and the measured data. The equation appears to bracket the majority of the measured data.

4. Total force and pressure data fit a Gumbel probability distribution for the limited number of events collected (309 events).

5. Single sub-panel pressures do not follow the distribution as well as the average pressures over larger areas of the total force.

2.3 Rudder and Steering Gear Loads

2.3.1 Objective

The objective of this project was to measure the response of steering gear and rudders under icebreaking operations and develop design criteria to increase the safety and reliability of steering systems on icebreaking vessels.

2.3.2 Program Overview

There were three elements to this program, namely:

- the measurement, reduction and analysis of rudder and steering gear responses in ice onboard the USCGC POLAR STAR
- the re-analysis of available full scale data from other vessels, and
- the development of design guidelines for rudders and steering gear for icebreaking ships.

During the program a mathematical model of rudder-ice interaction was developed. In addition, the program included a brief analysis of damage reports from an earlier casualty to the POLAR STAR steering gear and sub-foundation.

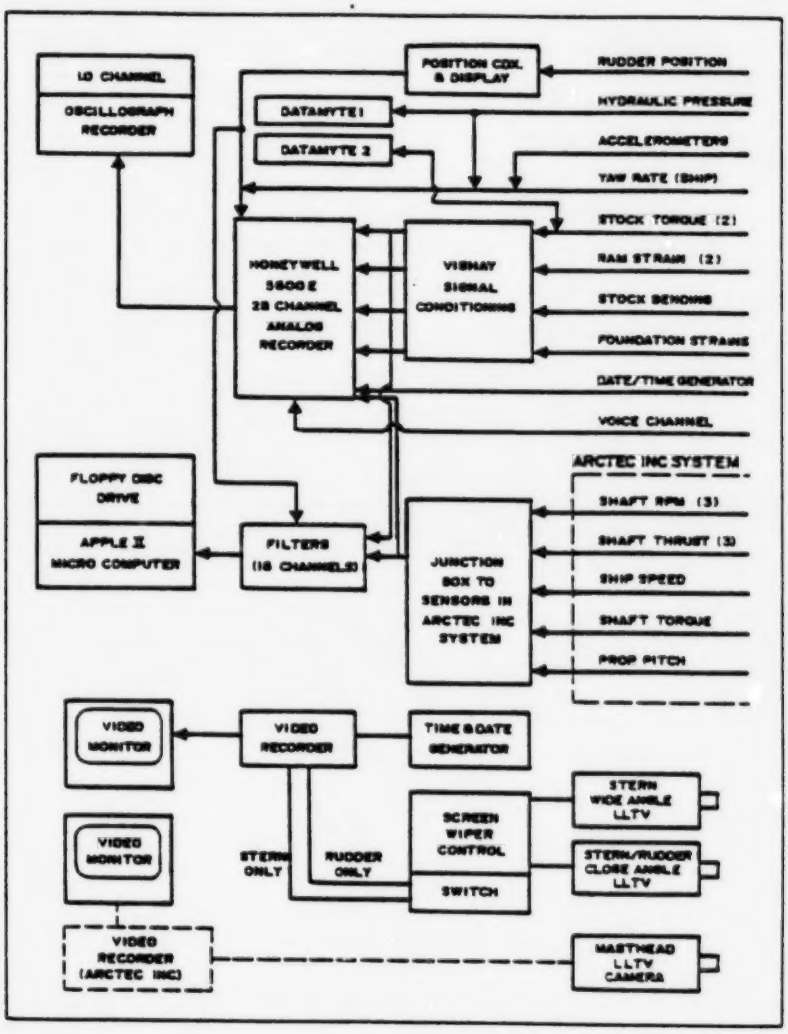
The POLAR STAR data collection took place in January 1982 during open water shake-down trials in Puget Sound, and during April and May 1982 when the ship was undertaking trafficability tests in ice in the Bering and Chukchi Seas off the West Coast of Alaska. The open water tests, consisting of zig zags, full turning circles and crash reversals were executed to test and calibrate the onboard instrumentation system and to establish a datum of hydrodynamic responses (used by designers) with which to compare ice induced responses. The tests in ice included turning, ramming,, backing down and other normal icebreaking manoeuvres in ice conditions up to 1.1 m thick first year ice with 2 m sail height ridges.

2.3.3 Measured Parameters

The instrumentation on the USCGC POLAR STAR consisted of sensors to measure strains due to torque and bending moment in the rudder stock and operating rams as well as the sub-foundation of the steering gear. In addition, rudder position indicators and accelerometers were fitted (Figure 2.12) and propeller shaft torque and thrust were recorded from existing sensors. A differential pressure transducer was fitted to the hydraulic system of the steering gear. A total of 36 channels of data were available for recording on one 28-channel FM analogue tape recorder.

FIGURE 2.12

INSTRUMENTATION BLOCK DIAGRAM



A masthead video system was installed and two additional low light level televisions (LLLTVs) in the environmental housings were deployed at the stern of the vessel. One of these cameras had a field of vision which covered the general conditions of the stern and permitted the overall assessment of the ice entering the stern area and ship speed to be made. The other camera provided a more detailed view of the area in the immediate vicinity of the rudder at the waterline. Seven analogue tapes containing 112 files with a total recording time of 116 hours work was obtained from the POLAR STAR.

In addition to the POLAR STAR data, four sets of previously recorded rudder load data were analyzed. This data included:

1) CCGS PIERRE RADISSON - data collected in summer of 1978 representing thickest ice conditions, up to 3 m thick. A total of 28 tapes representing 250 hours of recorded data, including propulsion system parameters, ice properties, rudder torque, steering ram strains and rudder angle.

2) CCGS LOUIS ST. LAURENT - thirty six hours of recorded data from backing and ramming in ice up to 1.7 m thick. Instrumentation consisted of ram gauges linked diagonally as on the POLAR STAR.

3) USCGC YANKTON 1974 - instrumentation measuring stock torque, and load cells measuring fore and aft and athwartship forces on two pintle bearings were installed. Rudder angle and ship speed measured, shaft speed noted manually. No calibration was performed therefore data given as a function of the maximum force recorded in open water tests. Only thin ice was encountered.

4) USCGC NAUGATUK - data available from tests in 1975 on rudder stock torque only, given as histograms of torque peaks under a number of different ship operating conditions.

2.3.4 Trials Results and Analysis

General

The principal measurements made and used in the analysis were rudder stock torque and bending strains. While additional parameters, specifically rudder stock accelerations and sub-foundation strains were recorded due to the availability of free recording channels, they were not analyzed under the scope of this contract and are identified in Section 4 as data suitable for further analysis if ship specific dynamic response is of interest.

A simple finite element model of the rudder and stock system of the POLAR STAR was built in order to estimate the order of magnitude of loads, and bending moments. However, since bending moment data was not available in the existing data base, the majority of analysis was undertaken on torque and bending strains.

For data analysis purposes, the data was grouped according to the following icebreaking modes:

(1) Backing and ramming,
(2) Backing in a broken channel,
(3) Manoeuvring ahead in ice,
(4) Continuous level icebreaking (ahead),
(5) Open water manoeuvring

The principal form of data analysis was statistical, as this permits direct comparison of statistically meaningful parameters for different data sets where not all parameters have been recorded in a comparable fashion.

In addition, analysis of the time series output from the sensors was carried out in some of the extreme events, to examine the quality and nature of the data, and evaluate the time dependent parameters such as strain rates, frequencies of oscillations, and phase relationships.

Finally, some specific detailed analysis of the most severe cases (backing and ramming) was undertaken for which maximum loads were estimated.

System Calibration

The system for measuring rudder stock strain was calibrated during open water manoeuvring tests on the POLAR STAR. A semi-empirical model was developed that calculated hydrodynamically induced stock torques as a function of speed, rudder angle, etc. The model includes such parameters as wake fraction, rudder area and effective aspect ratio. The comparison of measured and calculated torques was adequate at higher ship speeds to conclude that the recording system was correctly set-up and tuned, although there is room for improvement in the accuracy of the model.

Statistical Analysis

Statistical analysis focussed on probability distributions (histograms) of the peak ice impact torque to the maximum hydrodynamic (open water) torque. Figure 2.13 shows the probability distribution for the data measured in previous tests during ahead turning as well as backing and ramming. If the 'astern run' tests conducted with USCGC NAUGATUCK can be considered the 'backing' phase of a series of backing and ramming tests, it is seen from trials with all the three vessels that the highest torques in the rudder stock are experienced during the backing manoeuvres. The torque histogram for the POLAR STAR (Figure 2.14) also bears out the same conclusion. The maximum torque ratios can be listed as follows:

- CCGS RADISSON 5.38
- USCGC NAUGATUCK 3.77
- CCGS LOUIS ST. LAURENT 3.46
- USCGC POLAR STAR 3.96

Probability distributions for the POLAR STAR are shown in Figure 2.14. The hydraulic pressure histograms indicate that the relief valve pressures were not exceeded in any of the two series of tests.

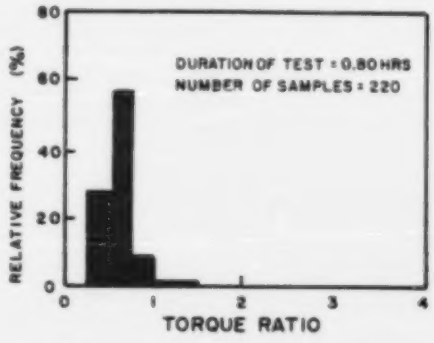
Time Series Analysis

Time series plots of the following parameters were generated for the ten cases identified where high rudder torques were recorded:

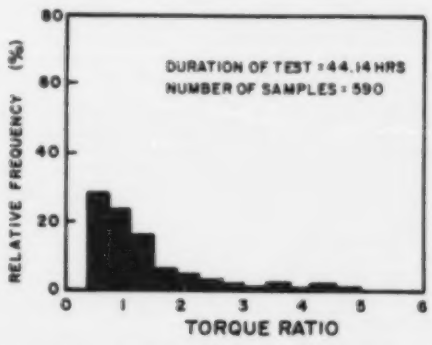
- Rudder Torque
- Rudder Hydraulic Pressure
- Rudder In-Plane Bending Strain
- Rudder Normal Load
- Rudder Tangential Load
- Ship Velocity
- Ship Yaw Rate
- Rudder Angle
- Rudder Normal Velocity
- Rudder Tangential Velocity
- Foundation Strain

An example of the data is shown in Figure 2.15 and full results are in Appendix E Volume IVA of report TP4125E [4].

CCGS RADISSON HYDRODYNAMIC REFERENCE TORQUE = 0.24 MN-m

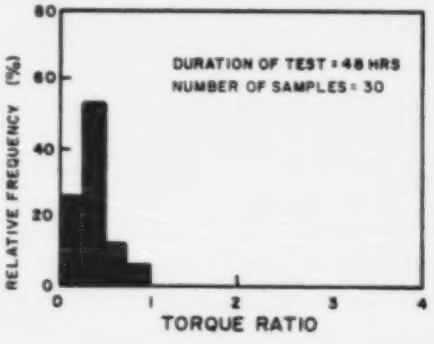


AHEAD TURNING IN .9m ICE 25° RUDDER
MAX. TORQUE = .36 MN-m
MEAN TORQUE = 0.15 MN-m

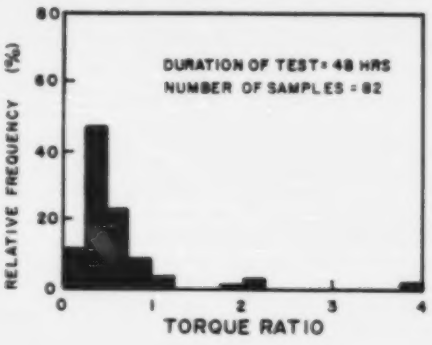


BACKING & RAMMING IN 2.1 m ICE
MAX. TORQUE = 1.29 MN-m
MEAN TORQUE = .34 MN-m

USCGC NAUGATUK HYDRODYNAMIC REFERENCE TORQUE = .025 MN-m

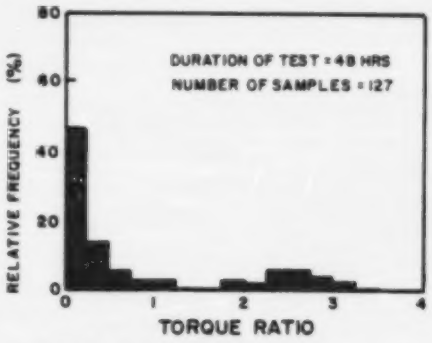


AHEAD TURNING
MAX. TORQUE = .02 MN-m
MEAN TORQUE = .010 MN-m



ASTERN RUNS
MAX. TORQUE = 0.09 MN-m
MEAN TORQUE = .014 MN-m

CCGS LOUIS S. ST LAURENT HYDRODYNAMIC REFERENCE TORQUE = .472 MN-m



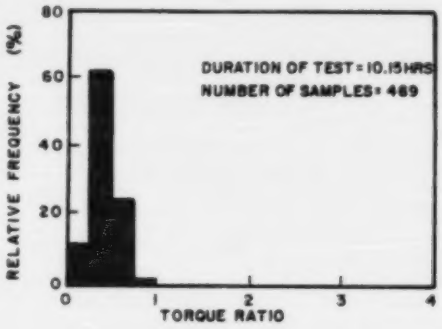
BACKING & RAMMING IN 1.6 m
MAX. TORQUE = 1.63 MN-m
MEAN TORQUE = 0.41 MN-m

FIGURE 2.13

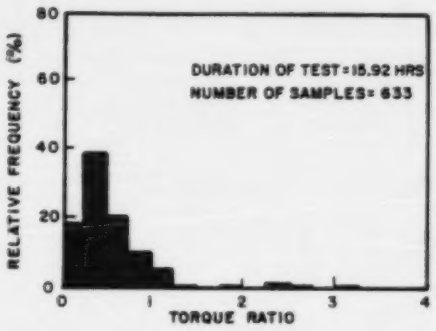
RUDDER STOCK TORQUE PROBABILITY DISTRIBUTION

USCGC POLAR STAR

MAXIMUM HYDRODYNAMIC REFERENCE TORQUE = .354 MN-m

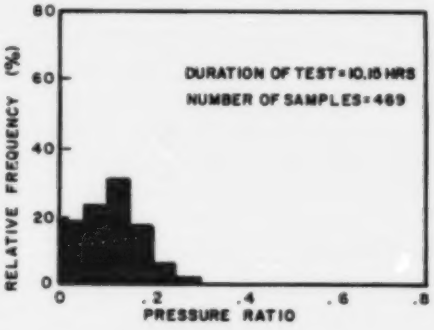


MANEUVERING AHEAD IN .4 m AT 7 KNOTS
MAX. TORQUE = 0.408 MN - m
MEAN TORQUE = 0.149 MN - m

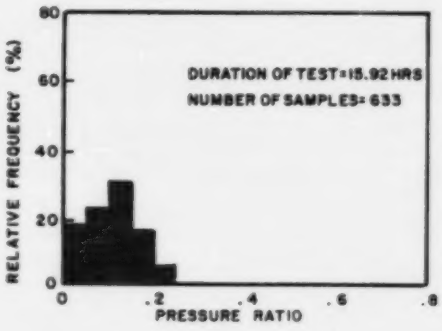


BACKING & RAMMING IN 1m ICE
MAX. TORQUE = 1.395 MN - m
MEAN TORQUE = 0.212 MN - m

RELIEF VALVE REFERENCE PRESSURE = 2000 psi



MANEUVERING AHEAD
MAX. PRESSURE 603 psi
MEAN PRESSURE 215 psi

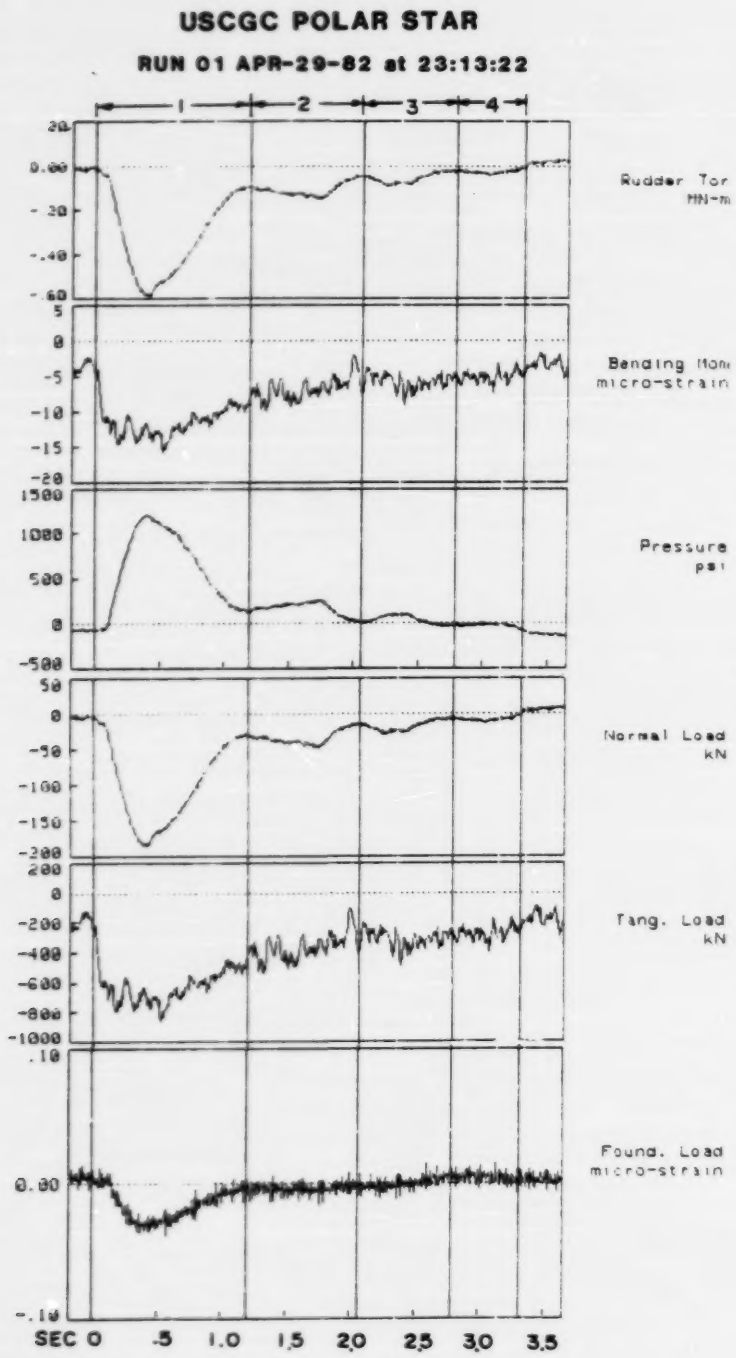


BACKING & RAMMING
MAX. PRESSURE 1146 psi
MEAN PRESSURE 255 psi

FIGURE 2.14
PROBABILITY DISTRIBUTION OF RUDDER STOCK TORQUE
AND HYDRAULIC PRESSURE IN STEERING GEAR

FIGURE 2.15

TYPICAL IMPACT
TIME HISTORIES



MEAN VALUES OVER THE ABOVE INTERVALS

TRANSDUCER	1	2	3	4	UNITS
Rudder Torque	-.31	-.11	-.05	-.02	MN-m
Bending Moment	-11.36	-6.63	-5.67	-5.04	Micro-strain
Pressure	619.93	167.47	37.94	-24.78	psi
Normal Load	-90.15	-33.19	-16.81	-7.66	kN
Tang. Load	-620.33	-361.82	-309.31	-275.43	kN
Found. Load	-.01	-.00	0.00	0.00	micro-strain

PEAK VALUES WITHIN THE ABOVE INTERVALS

Rudder Torque	-.58	-.15	-.09	-.04	MN-m
Bending Moment	-15.84	-9.83	-9.01	-7.28	micro-strain
Pressure	1200.45	256.14	108.01	-97.21	psi
Normal Load	-183.62	-46.94	-28.23	-13.64	kN
Tang. Load	-864.62	-536.80	-491.73	-397.48	kN

Detailed Analysis of Backing and Ramming Cases

The relative magnitudes of bending and torsion strains in the rudder stock were investigated. The strain ratio of bending to torque was found to be low at high rudder torques, increasing slightly as torque decreased.

The flexural load was determined from the flexural strains using the STARDYNE finite element program. This model was considered sufficiently rigorous to determine the order and spread of maximum bending moments, as well as examine sensitivity of the results to assumptions such as load point and rudder stiffness. Two curves were produced representing extremes of bending moment in the section of the rudder stock where the bending gauge was located (see Figure 2.16). The maximum bending moment in the rudder stock ranged from 7150 to 18,500 Nm.

From the rudder stock torsion and bending strains, ship speed, yaw rate and rudder angle, both the normal and inplane loads on the rudder were calculated. Table 2.7 relates ice loads measured to hydrodynamic loads. It can be seen that normal ahead ice loads on the rudder are about twice the magnitude of hydrodynamic loads, and astern loads of the same magnitude as the hydrodynamic loads, while in-plane loads, ahead and astern, are three times the hydrodynamic loads.

Math Model of Ice Impact Loads

A computer model was developed to predict rudder stock loads and torques arising from typical rudder-ice floe impact situations. The output of the model is maximum rudder load and torque, along with the impact duration. Details of this math model are given in Appendix C of Volume IVA [4]. The primary use of the model for the designer is in assessing the sensitivity of design parameters (such as torque) to changes in system parameters (such as stock diameter).

A comparison of maximum rudder torque and rise time between the measured results and math model was carried out for eight selected full scale test cases. The cases were selected because they represented a range of rudder-ice interaction scenarios, and the ice flowing into the rudder could be well characterized (size, speed, position) from the video records. Two ice strengths and two ice thicknesses were used for the model which covered a range of values around the ice parameters (observed by video for each test case). The results of this comparison show fairly good agreement for both measured rudder torque and torque rise times. A very short 'rise time' (time for signal to reach 90% of peak value from start of event) is associated with large torques, leading to a concern that the steering gear would not be able to respond fast enough to relieve the load through the pressure relief valve. Pressures above the relief valve normal setting were not encountered in these trials, and therefore no assessment of the steering gear response characteristics beyond the relief point could be made.

FIGURE 2.16
STATIC STRUCTURAL MODEL of POLAR STAR RUDDER for IN-PLANE BENDING

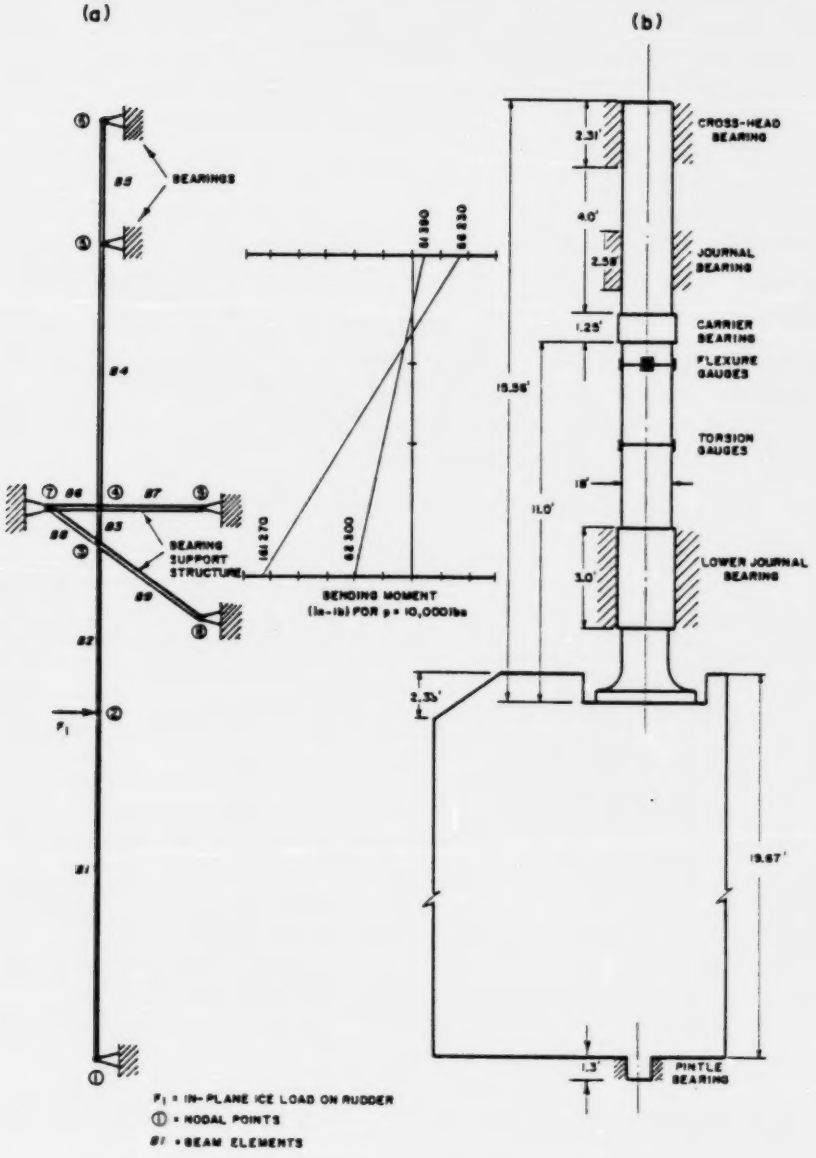


TABLE 2.7
RANGE OF HYDRODYNAMIC LOADS

DIRECTION	VELOCITY (m/sec)		ICE LOAD (kN)		MAXIMUM AHEAD HYDRODYNAMIC LOAD (kN)
	AHEAD	ASTERN	AHEAD	ASTERN	
Normal	2.1	0.65	330	120	145
In-plane	6.0	1.8	340	275	82

2.3.5 Design Guidelines on Rudder Stock Sizing and Optimum Rudder Configuration

A set of design oriented rudder torque curves were developed based on a dimensional analysis of the torques measured during the backing and ramming trials of the four vessels discussed in Section 2.3.3. These are presented in Figure 2.17 as dimensionless torque versus rudder stock length/diameter ratio.

The lowest dimensionless torque was registered by the POLAR STAR which has the highest rudder stock length/diameter ratio. This indicates that length as well as diameter must be considered in rudder stock design.

These curves allow a simple design procedure to be carried out. An alternative method would be to use the math model simulation program, developed in this project, providing all the necessary inputs are available.

From data collected in the backing and ramming mode for the four vessels it was determined that the number of impacts between the rudder and ice was greater for rudders with less immersion (i.e. smaller operating draft, see Table 2.8. An important conclusion drawn from this is that a margin of safety in rudder ice strengthening can be obtained by controlling the vessel operating draft.

NON-DIMENSIONAL REPRESENTATION OF RUDDER-ICE IMPACT TORQUES

OPERATION - BACKING & RAMMING

Q_R = REACTION TORQUE IN RUDDER STOCK
h = ICE THICKNESS
r = DISTANCE FROM RUDDER STOCK AXIS TO TRAILING EDGE OF RUDDER
ℓ = LENGTH OF RUDDER STOCK FROM CROSS HEAD TO RUDDER PALM
d_R = DIAMETER OF RUDDER STOCK
G = RIGIDITY MODULUS OF STOCK

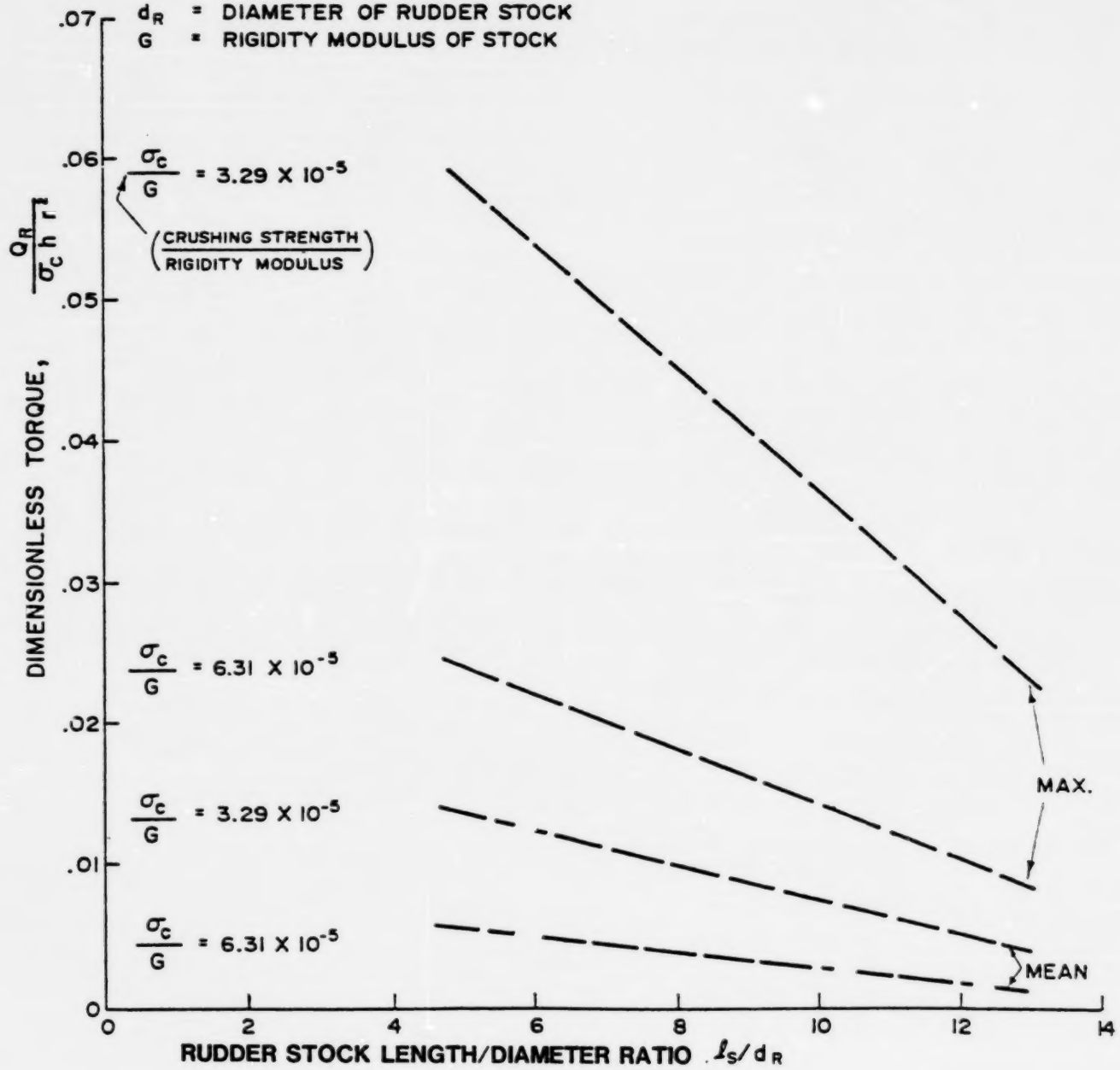


FIGURE 2.17

TABLE 2.8

FREQUENCY OF IMPACTS FOR BACKING AND RAMMING

VESSEL	DRAFT AT RUDDER STOCK	ICE THICKNESS RANGE	NO. OF IMPACTS/HR
USCGC POLAR STAR	1.52 m	0.9 m	54.1
CCGS PIERRE RADISSON	2.13 m	2.5-1.8 m ridges	30.6
CCGS LOUIS ST.LAURENT	2.80 m	1.7-1.5 m	12.65*
USCGC NAUGATUK	0.86 m***	0.4-2.25 m with ridges up to 1.5 m	16.2**

* Includes all torque over 0.134 MN.m

** At the time of recording, the vessel was performing escort service and was not backing and ramming 100% of duration.

*** Includes rudder/ice impact data for all cases and duration of each test is not accurate. Draft estimate based on best available information.

2.3.6 Conclusions from the Steering Loads Report (1982)

The following general conclusions were drawn as a result of the data collected during the 1982 trials of the POLAR STAR, and re-analysis of data from other vessels.

- Backing and ramming generates the highest loads on the system. Contrary to popular notions, the ahead mode during ramming operations also results in a large number of significant impacts on the rudder. The majority of the impacts occuring in the ahead mode are associated with large rudder angles, both port and starboard, probably due to the ship manoeuvring to 'best' ramming location.

- Maximum torques on the rudder stock occuring during backing and ramming may be much in excess of hydrodynamic torques. Torque ratios as high as 3 to 4 have been recorded in ice conditions below extreme cases.

- Bending moments in the stock due to inplane loading lead to strains in the stock which are generally much less than those induced by torque.

- A semi-empirical model of hydrodynamic loads on rudders has been developed, and has shown to be quite accurate in its predictions. This model may be used as a standard for comparison of basic rudder design.

- The mathematical model of rudder ice impact has been verified to a considerable extent under the present contract. To improve accuracy, refinement of load and crushed area relationships are needed.

- Based on the full scale data from trials with four different ships, a method of determining the ice strengthening required in the sizing of rudder stocks is given. It is shown that sizing of the diameter of rudder stock independent of its length is not adequate for ice loads.

- Assembly of available full scale data results in other vessels confirmed lack of qualifiable data on rudder and steering loads. The data base finally consisted of two USCG and two CCG icebreakers with the CCGS PIERRE RADISSON forming the greatest quality of full scale data and the thickest ice conditions.

3. MANOEUVRING PERFORMANCE

3.1 Objectives

The objectives of the test program are given below:

- Quantify the manoeuvring capability of the Polar Class vessels in ice as a function of ship speed and rudder angle in 3 to 6 feet (0.9 to 1.8 m) of level first year ice.

- Obtain manoeuvring data for the Polar class vessels in a form useable in the development and verification of a manoeuvring simulation model.

- Develop and demonstrate a standard methodology for the conduct of full scale icebreaking manoeuvring tests, including a standard data collection and processing system.

3.2 Ice Cover

Measuring the manoeuvring performance of icebreakers at full scale has presented a number of important problems, particularly for ships whose deployments take them primarily into the North American Arctic. In these regions extensive ridging of the sea ice is common making it difficult to find the large expanses of uniform level ice which are needed to execute turning circle arcs of 180 degrees or more. It was recognized that the annual deployment of a Polar Class icebreaker to McMurdo Sound in the Antarctic presented a unique opportunity to obtain full scale manoeuvring data in an ideal ice environment, (Figure 3.1). McMurdo Sound affords one of the best natural sites in the world for the conduct of icebreaking tests in uniform level ice. At the time of the ship's arrival, the Sound typically contained more than 250 square kilometres of level, ridge-free shorefast ice, varying smothly from about 1.6 m in thickness at the south end of the Sound to about 0.9 metres in thickness six kilometres to the north at its seaward edge.

3.3 Measured Parameters

The parameters recorded were the following:

1. Port Propeller Shaft Thrust
2. Centre Propeller Shaft Thrust
3. Starboard Propeller Shaft Thrust
4. Ship's Speed
5. Ship's Heading
6. Rate of Change of Ship's Heading
7. Rudder Angle
8. Range to Arrival Heights Positioning Base Station
9. Range to Tent Island Positioning Base Station
10. Time at End of Scan.

Throughout the manoeuvring tests, the ship's position was determined once per second by measuring the ranges from the ship to two shore-fixed base stations.

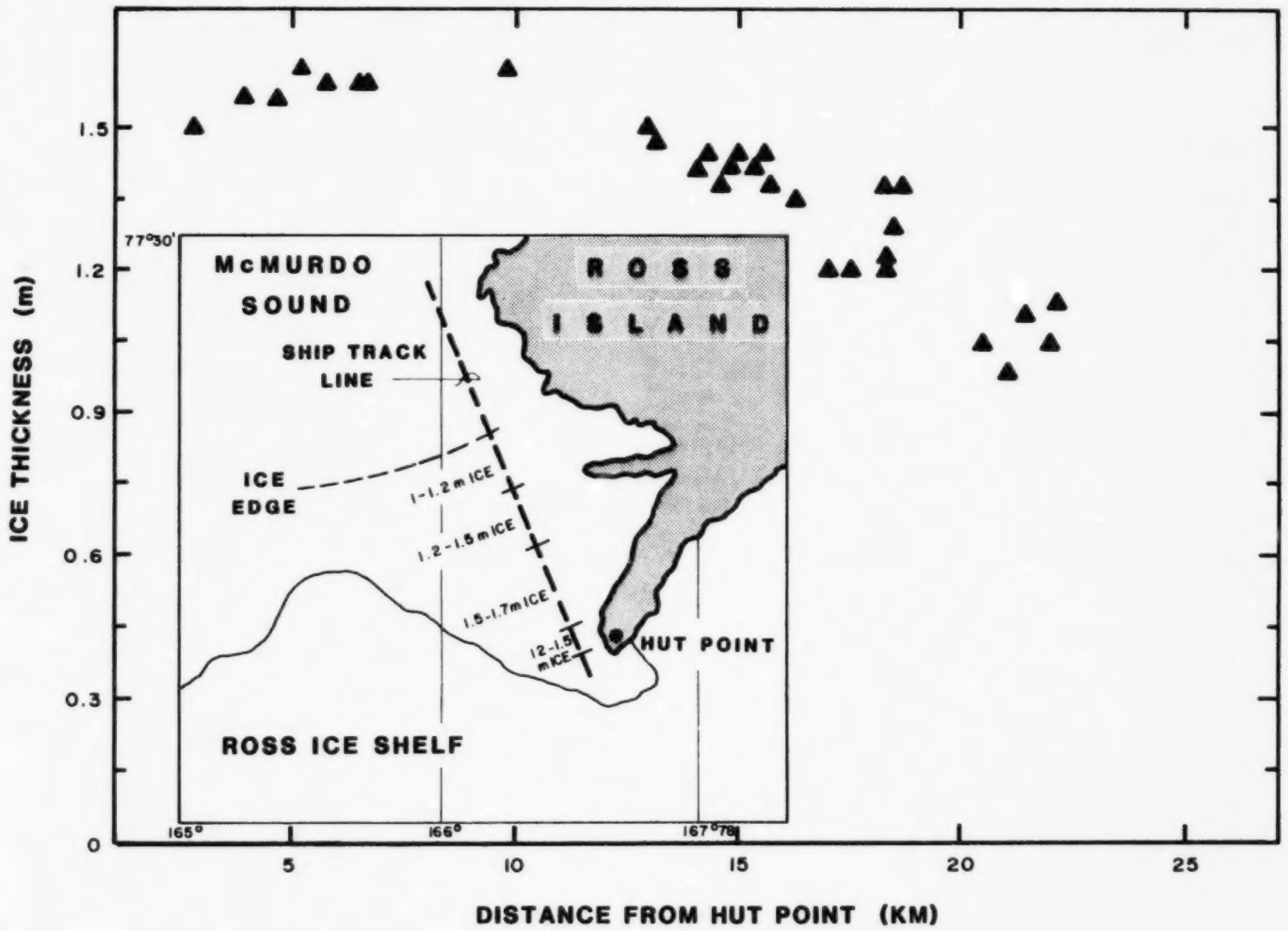


Figure 3.1 **AVERAGE ICE THICKNESS from ICE EDGE to HUT POINT**

3.4 Conduct of Manoeuvring Tests

The manoeuvring tests of the POLAR STAR were conducted as a series of "S" turns, that is arcs or sectors of about 180 degrees executed back to back. Throughout each such arc the pitch order and rudder angle were held constant at the desired level until the required change in heading had been obtained. The test arcs were limited to about 180 degrees in order to avoid the anomalous results that can be obtained when the ship begins to approach its own track causing splitting and breakup of the ice pan left in the centre of the turn.

During these tests the POLAR STAR was at a relatively light draft, having onboard only some 360,000 gallons of fuel oil. The ship's ballast conditions is summarized in Table 3.1. Throughout these tests the steering system appeared to be in good working order and functioned normally at all times. Difficulty was experienced, however, in obtaining and maintaining desired pitch settings on both of the wing propellers. Despite ordering equal pitch settings, these two shafts typically exhibited significantly different and highly variable thrust, with the starboard propeller usually developing more thrust than the port one. Tests 1 to 3 inclusive were done using 2 diesels to power each shaft for a nominal maximum output of 18,000 HP. Tests 4 and 5 were done with two diesels powering each wing shaft and a gas turbine powering the centre shaft for a total of 32,000 HP maximum.

The matrix of test points obtained in these tests is shown in Table 3.2. The table illustrates the test program by port and starboard turns. Note that the "1/3, 1/2" designation does not refer to the engine power level, but rather is an indication of the nominal available SHP. Figure 3.2 and 3.3 show typical vessel trajectories recorded during the tests.

3.5 Analysis of Manoeuvring Data

The test data can be categorized in groups as follows:

GROUP	TESTS	ICE THICKNESS	THRUST DISTRIBUTION
A	1/2, 1/3	1.12 m	30/40/30
B	2/1, 2/4	0.93 m	12/55/33
C	3/1, 3/4	0.93 m	18/38/45
D	4/1, 5/4	1.49 m	5/90/5

From reviewing the data, the following trends can be noticed:

- The turning radius for port turns is smaller than for starboard turns, even when the thrust distribution is balanced. This can be seen by comparing tests 1/2 and 1/3 and tests 5/1 and 5/2 where the difference in R/L is 1.6 to 2.2.

- Higher loading on the centre propeller produces a smaller turning radius. Compare tests 2/2 and 3/1 and tests 2/3 and 3/4.

TABLE 3.1

LOADING CONDITION OF USCGC POLAR STAR DURING ANTARCTIC MANOEUVRING TESTS, JANUARY 1985

Draft Forward	25.0 feet (7.62 m)
Draft Aft	27.0 feet (8.22 m)
Waterline Length (at these drafts)	337.5 feet (102.87 m)
Max. Beam at Waterline	76.0 feet (23.16 m)
Design Draft	28.0 feet (8.53 m)
Design Waterline Length	352.0 feet (107.29 m)

TABLE 3.2

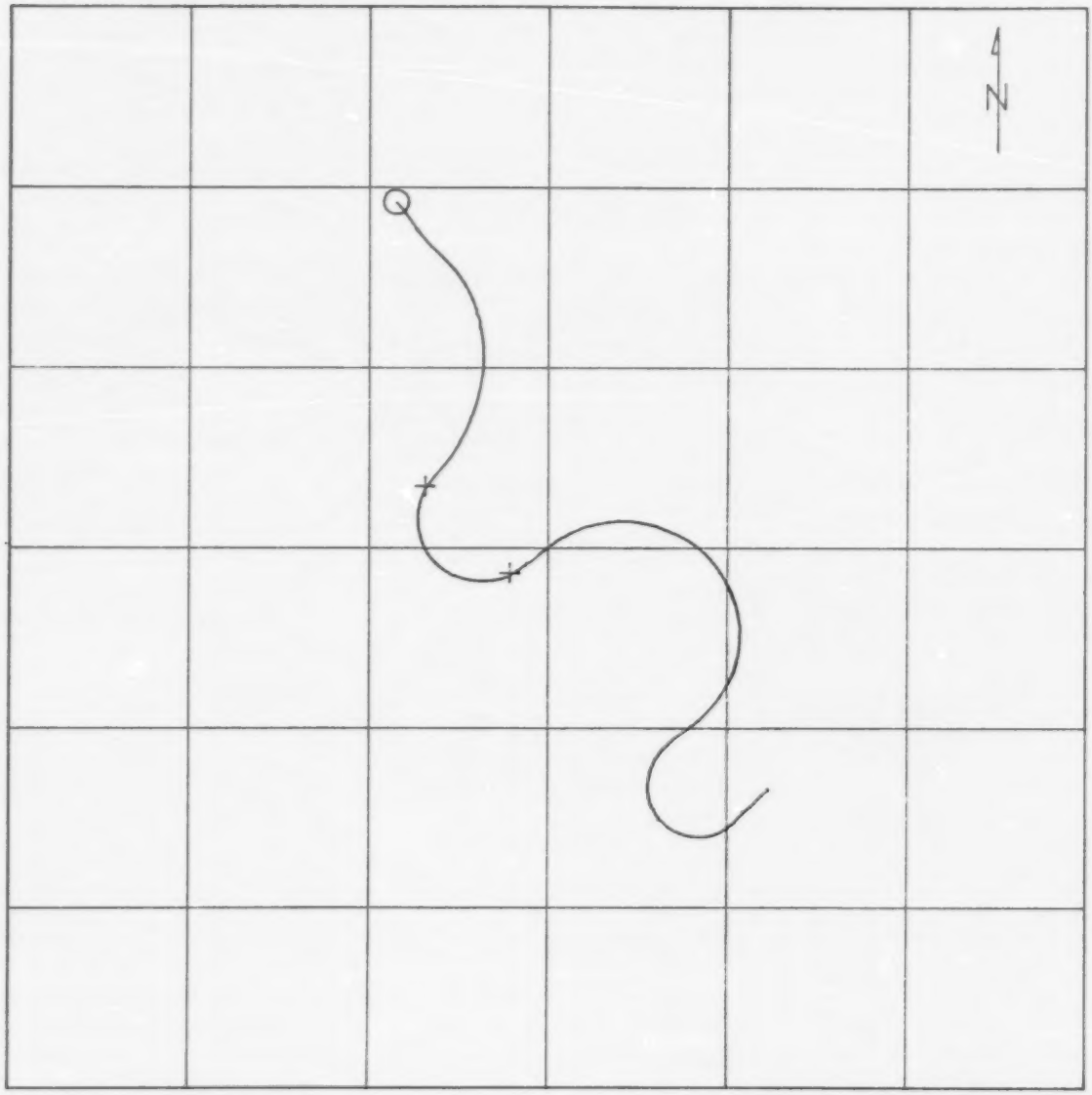
REVIEW OF TEST DATA

TEST SECTOR	δo DEG.	δa DEG.	P/S TURN	V m/sec	hi m	T_{total} kN	P %	C %	S %	R/L
1/1	10.0	10.3	S	2.8	1.12	924	39	26	36	23.8
1/2	20.0	20.0	S	2.5	1.12	1106	24	39	37	6.4
1/3	20.1	19.0	P	2.3	1.12	1198	35	43	22	4.2
2/1	20.0	17.1	S	2.7	0.84	929	4	60	36	8.4
2/2	20.0	20.0	P	2.1	0.93	898	16	55	29	3.7
2/3	25.0	21.8	S	2.3	0.93	1023	8	55	37	7.2
2/4	25.0	25.8	P	1.8	1.02	1010	18	50	31	3.2
3/1	20.0	21.4	P	2.3	1.02	831	23	42	34	4.1
3/2	25.0	23.4	S	2.2	0.93	836	14	36	50	8.1
3/3	15.0	17.3	P	2.4	0.93	823	23	35	42	5.3
3/4	25.0	21.9	S	2.6	0.84	790	11	38	52	8.6
4/1	20.0	21.7	S	2.0	1.63	1506	3	84	13	5.4
4/2	15.0	15.1	P	1.7	1.49	1216	9	96	6	3.5
4/3	20.0	22.4	S	2.1	1.49	1438	2	89	9	4.3
4/4	15.0	10.6	P	1.7	1.35	1175	11	88	1	3.9
5/1	20.0	19.3	P	2.5	1.35	1214	8	91	0	3.7
5/2	20.0	19.0	S	2.3	1.49	1446	3	86	11	5.3
5/3	15.0	13.6	P	2.5	1.49	1221	6	93	0	4.1
5/4	20.0	18.3	S	2.3	1.63	1454	3	88	10	4.4

USCGC POLAR STAR

JANUARY 1985 MANOEUVERING TESTS

TEST 2 SECTOR 2 22 Jan 1985



GRID SPACING 1000 meters

START LOCATION ○

SECTOR DELIMITER +

FIGURE 3.2

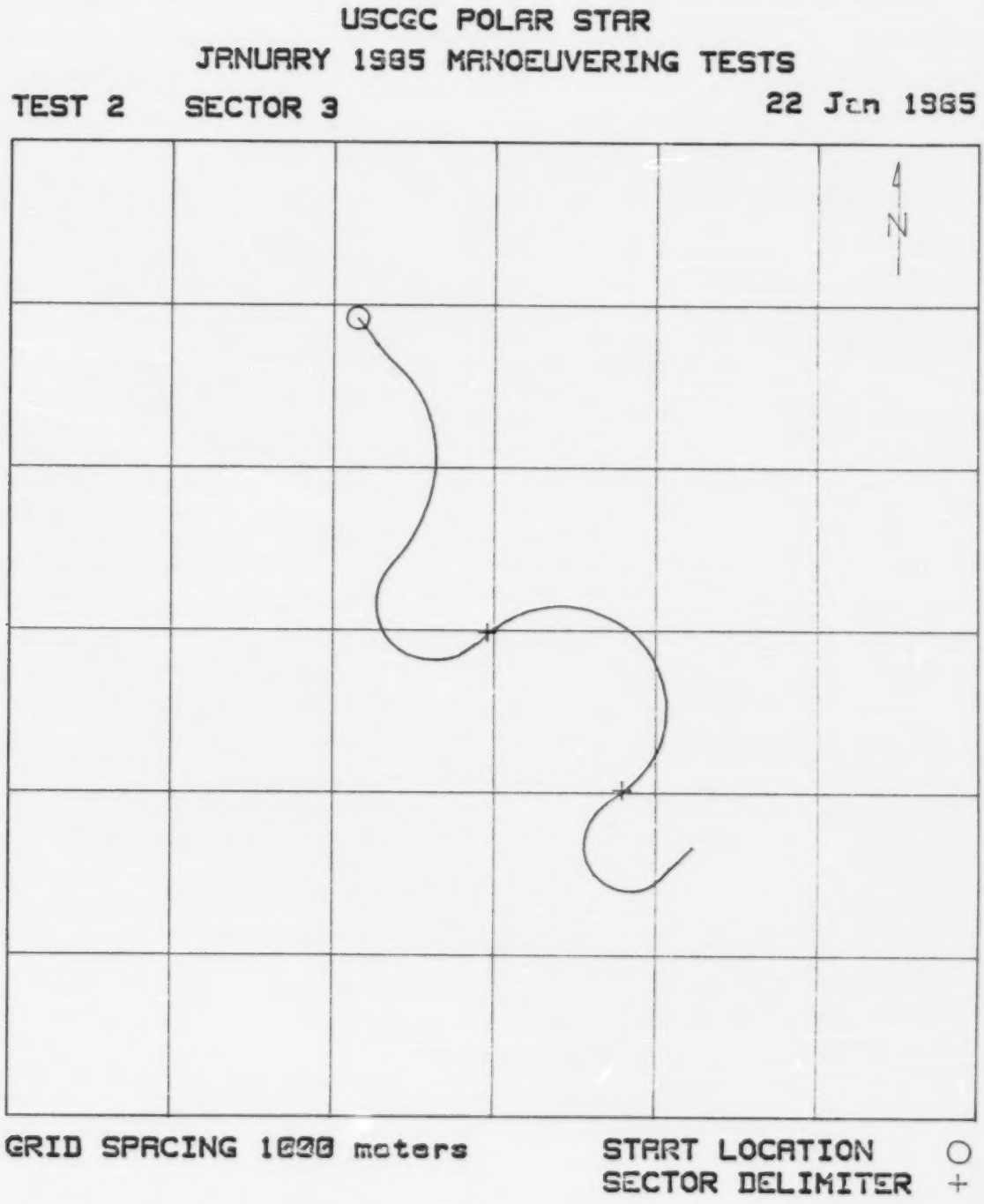

USCGC POLAR STAR
JANUARY 1985 MANOEUVERING TESTS
TEST 2 SECTOR 3
22 Jan 1985
N
GRID SPACING 1000 meters
START LOCATION
SECTOR DELIMITER

FIGURE 3.3

- The speeds were maintained fairly constant throughout the trials. In thicker ice, however, a higher thrust was required, which in turn increased the rudder effectiveness. Furthermore, the centre propeller developed 90% of the thrust in Group D. Therefore, the radius to length ratios were lower in these tests. When extrapolating the average R/L of Groups C (38% centre shaft thrust) and B (55% centre shaft thrust) to the same thrust distribution as Group D with 90% thrust on the centre shaft, see Figure 3.4, the trend of Figure 3.4 was obtained for a rudder angle of 20 degrees. Plotting the average R/L of Group A with 40% thrust at the centre shaft, it is clear that this test was conducted in rather weak ice.

- The turning tests at 15 degrees rudder angle in Group D show rather low values of R/L compared to the values for the 20 degree rudder angle. All these turns to port, in general, produced lower R/L values. The average R/L for 15 degrees rudder angle to port is 3.83. If we define the band of asymmetry as the absolute value of the difference between the R/L port and starboard, then adding half the asymmetry band to R/L = 3.83 will give a value of R/L = 4.63. The average R/L for 20 degrees helm is 4.35. The magnitude of the asymmetry band and the imbalance in the thrust distribution have been estimated and are plotted in Figure 3.5.

- The standard deviation between the ordered and actual measured helm is about 2.0 degrees. Three of the four ordered 25 degrees helm result in lower actual helm. When test 2/4 is considered, 26 degrees helm, the port turn R/L of 3.2 would give the bandwidth of Figure 3.5 and average port and starboard turn R/L of 4.95, which with Figure 3.5 extrapolated to 90% centre shaft thrust would give a value for R/L of 3.1. Similarly, for tests 3/3, a value for R/L of 4.4 is obtained for a rudder angle of 17 degrees. The results are plotted in Figure 3.5.

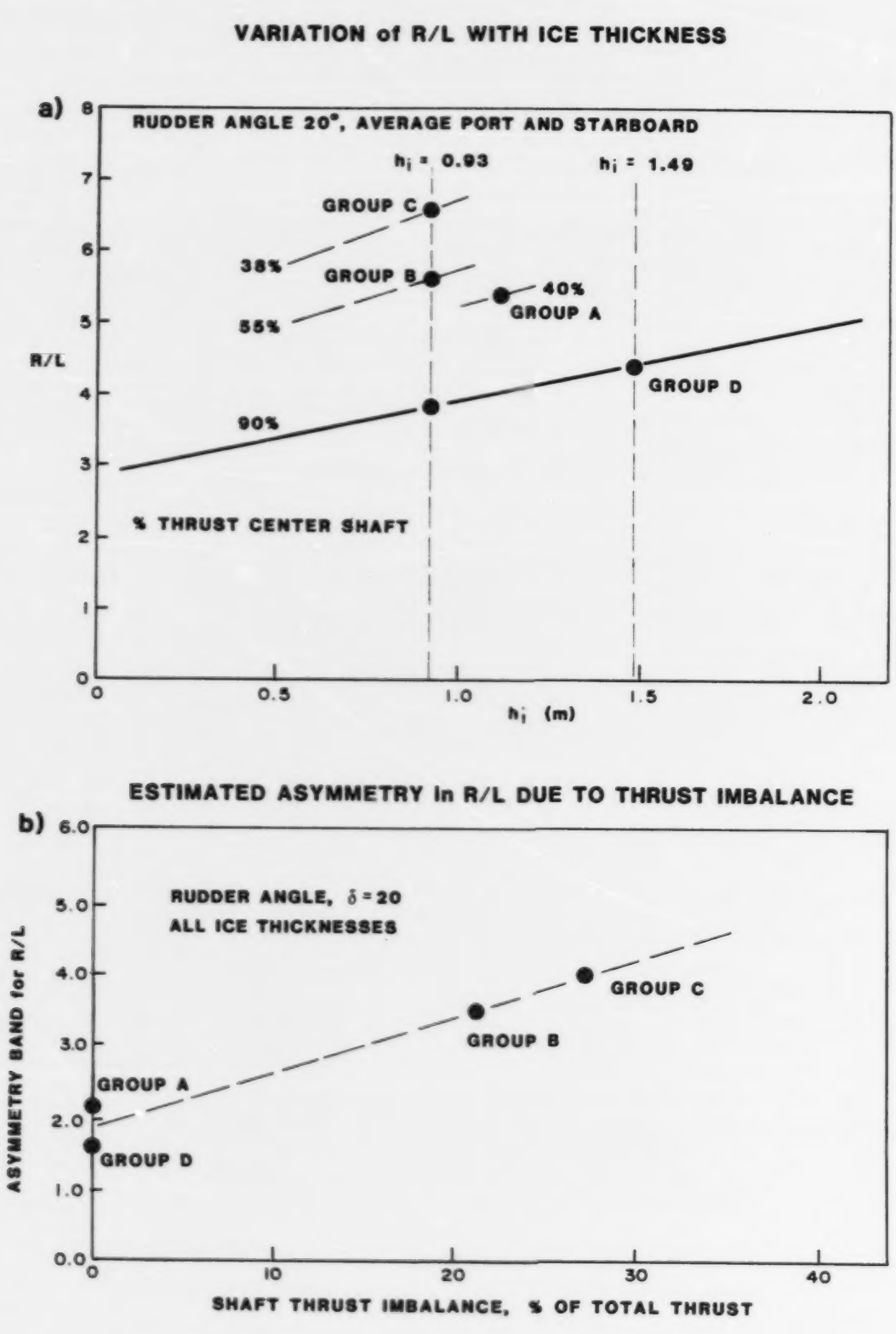

VARIATION of R/L WITH ICE THICKNESS
a)
RUDDER ANGLE 20°, AVERAGE PORT AND STARBOARD
h_i = 0.93
h_i = 1.49
GROUP C
38%
GROUP B
40%
55%
GROUP A
R/L
GROUP D
90%
% THRUST CENTER SHAFT
h_i (m)
ESTIMATED ASYMMETRY In R/L DUE TO THRUST IMBALANCE
b)
RUDDER ANGLE, δ = 20
ALL ICE THICKNESSES
ASYMMETRY BAND for R/L
GROUP C
GROUP B
GROUP A
GROUP D
SHAFT THRUST IMBALANCE, % OF TOTAL THRUST

FIGURE 3.4

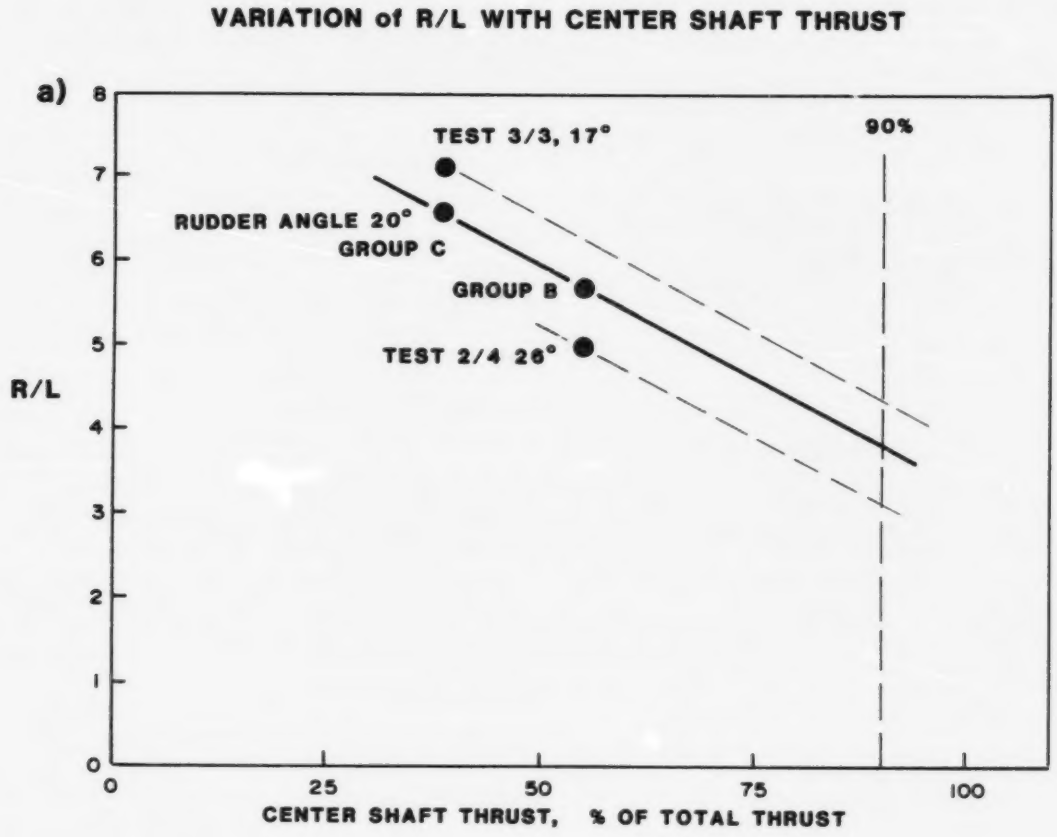

VARIATION of R/L WITH CENTER SHAFT THRUST
a)
TEST 3/3, 17°
90%
RUDDER ANGLE 20°
GROUP C
GROUP B
TEST 2/4 26°
R/L
CENTER SHAFT THRUST, % OF TOTAL THRUST
VARIATION of R/L WITH RUDDER ANGLE
b)
R/L
90% THRUST AT CENTER SHAFT
ICE THICKNESS : 0.93m
RUDDER ANGLE (DEG.)

FIGURE 3.5

3.6 Conclusions

From the above analysis, a number of conclusions were arrived at and are discussed below:

i) In addition to the standard variables such as rudder angle, ice thickness and ship speed, the propeller thrust has a significant influence on the manoeuvring capabilities of the POLAR STAR.

ii) The effect of propeller thrust on steady turning can be divided into three categories: total thrust which governs the straight-ahead icebreaking and hence the turning capabilities, the distribution of the thrust between the three shafts which determines the rudder effectiveness and thirdly, the thrust imbalance between the shafts which introduces asymmetry in the port and starboard turns.

iii) Based on the data analysed and the factors described above, it can be shown that for a given total thrust the difference between the R/L port and starboard can be as high as 100%.

iv) It seems that the most effective manoeuvring method will involve developing 90% of the total thrust on the centre shaft.

4. IDENTIFICATION OF DATA FOR FURTHER ANALYSIS

4.1 Introduction

During the several years of extensive trials performed onboard the USCGC "POLAR" Class vessels, a considerable amount of vessel performance and hull response data were collected along with corroborating environmental information. In general, at the end of each series of trials, the bulk of the collected data were reduced and analyzed and a report prepared. The remainder of the data were archived for future use and were stored in readily accessible formats. In the course of the review and consolidation task, reported in the previous sections, a few aspects of the trials were identified as belonging to the second category. No previous analysis of this data has been made partly because the data was collected on an opportunity basis and was not directly required for the completion of the projects. In addition, further analysis of re-analysis of data collected may also be of advantage and is discussed herein.

4.2 Ice Induced Vibrations

4.2.1 Introduction

The data which has been identified as showing promise for analysis can be grouped under two general headings; structure and machinery. Deck strains were recorded during the 1981 trials of the POLAR SEA. It had been hoped that analysis of this strain data could be used to predict the forces occurring at the bow which created these strains; however, a brief study of this data shows that this will not be possible.

During the same 1981 trials, time histories of thrust, torque, RPM, and pitch for all three shafts were recorded over a 160 hour period. Using this data to study propeller ice milling incidents it may be possible to determine the forces between the propeller blades and ice blocks.

This data has been examined briefly, to determine what data actually exists, how useful this data may be and to suggest methods of analysis which will make the best use of this data.

4.2.2 Hull Strain Gauge Measurements

Hull and deck strain gauges, located as indicated on Figure 2.1 earlier, were monitored during the 1981 POLAR SEA trials. Unfortunately two problems prevent this data from being useful. First, the gauges were mounted without temperature compensating "dummy" gauges. As a result the calibration constants for the deck gauges which may have been subjected to significant daily temperature changes may be inaccurate.

A more important and limiting problem arose when a preliminary analysis of data tapes showed no significant response from the strain gauges when either breaking level ice, or ramming pressures ridges. In the case of gauges mounted in the bilge area, difficulty in locating the gauges on a suitable member that would experience total hull bending strains, plus the structural 'noise' from the machinery rendered the data useless. The deck gauges - mounted on the webs of deck longitudinals also showed little response and it must be assumed that they were placed either at a local nodal point of the hull response, or that they were not correctly installed. As a result analysis of the data from the deck and hull strain gauges is not expected to show any useful result. Samples of the strain gauge outputs from an oscillograph for open water and while ramming a ridge are shown in Figures 4.1 a and b.

No further analysis of the midship strain gauges is recommended. However, using the techniques developed further in the VTT/German and Milne tests of the MV ARCTIC, some correlation between bow accelerometer read out and peak force should be achievable and further analysis of this is suggested.

4.2.3 Shaft Measurements

Time histories of torque, thrust, RPM, and pitch were recorded for the centreline and two wing shafts during the 1981 POLAR SEA trials [1]. A preliminary analysis of a sample of this data has been made to determine what information can be determined.

The tapes containing time histories of torque, thrust, RPM, and pitch for the three shafts were played back and their output printed on an O-graph. Some problems arose with the data, the first problem being large zero drifts throughout the study. As a result, the mean value of torque and thrust could not be accurately determined; however, the following information could be estimated:

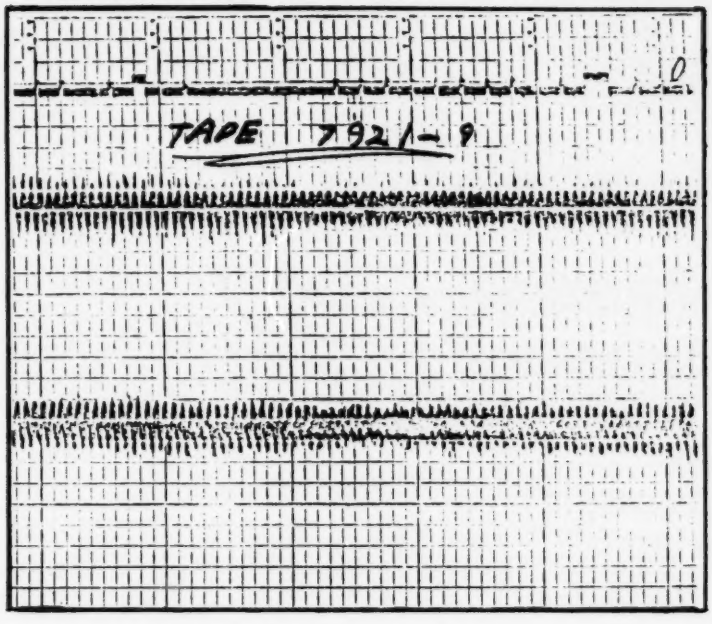
19 Percentage variation from mean thrust and torque levels.
2) The duration of each propeller-ice interaction.
3) Relative amount of interaction on each shaft.
4) Modes of operation in which propeller-ice interactions occurred.
5) Frequency of oscillation of thrust and torque.
6) Estimates of the propeller ice load.

In addition to the 160 hours of data collected onboard the POLAR SEA, thrust torque, RPM and pitch were also recorded onboard USCGC POLAR STAR during the 1982 winter trafficability studies [10]. To date no analysis has been made of this data which was collected in a very similar manner to that onboard the POLAR SEA in 1981.

FIGURE 4.1

OUTPUT FROM DECK MOUNTED STRAIN GAUGES

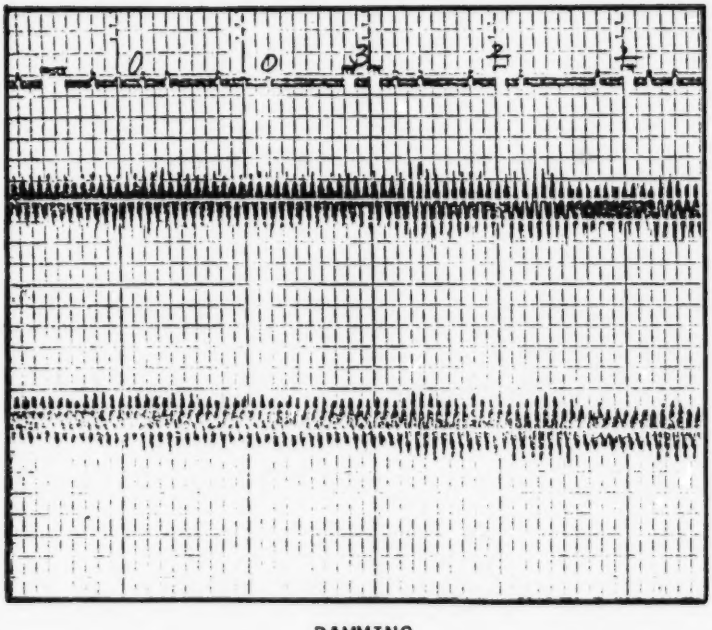
a)



S_1

STEADY STATE

b)



S_1

S_2

RAMMING

Based on the description of the performance of the instrumentation in Volume V of the 1982 POLAR Class report [10] it appears that shaft torque, pitch and RPM were measured satisfactorily with no problems; however, the thrust gauges suffered from zero drift as a result of temperature changes. While the accuracy of this measurement is described as acceptable when zero drift is accountd for, it is possible that steady state thrust values may not be obtainable as was the case in the 1981 data. It is probable that the 1982 POLAR STAR data is of at least as high quality as the 1981 POLAR SEA data.

As the two vessels are identical sisterships it is very likely that these two data sets can be combined and treated as one large set.

One case of propeller-ice interaction was analyzed to demonstrate the type of data available. The vessel was in the astern model during a ramming sequence in three feet of ice. The variation of torque and thrust during ice/propeller interaction for the starboard, centreline, and port shafts are shown in Figure 4.2, 4.3, and 4.4. Table 4.1 describes the results of analyzing these figures. These results indicate that the centre shaft had negligible ice/propeller interaction, but the starboard and port shafts did. The variation of pitch during this ice/propeller interaction is shown in Figure 4.5. There are some transient vibrations in the pitch signal as the reverse pitch is increased.

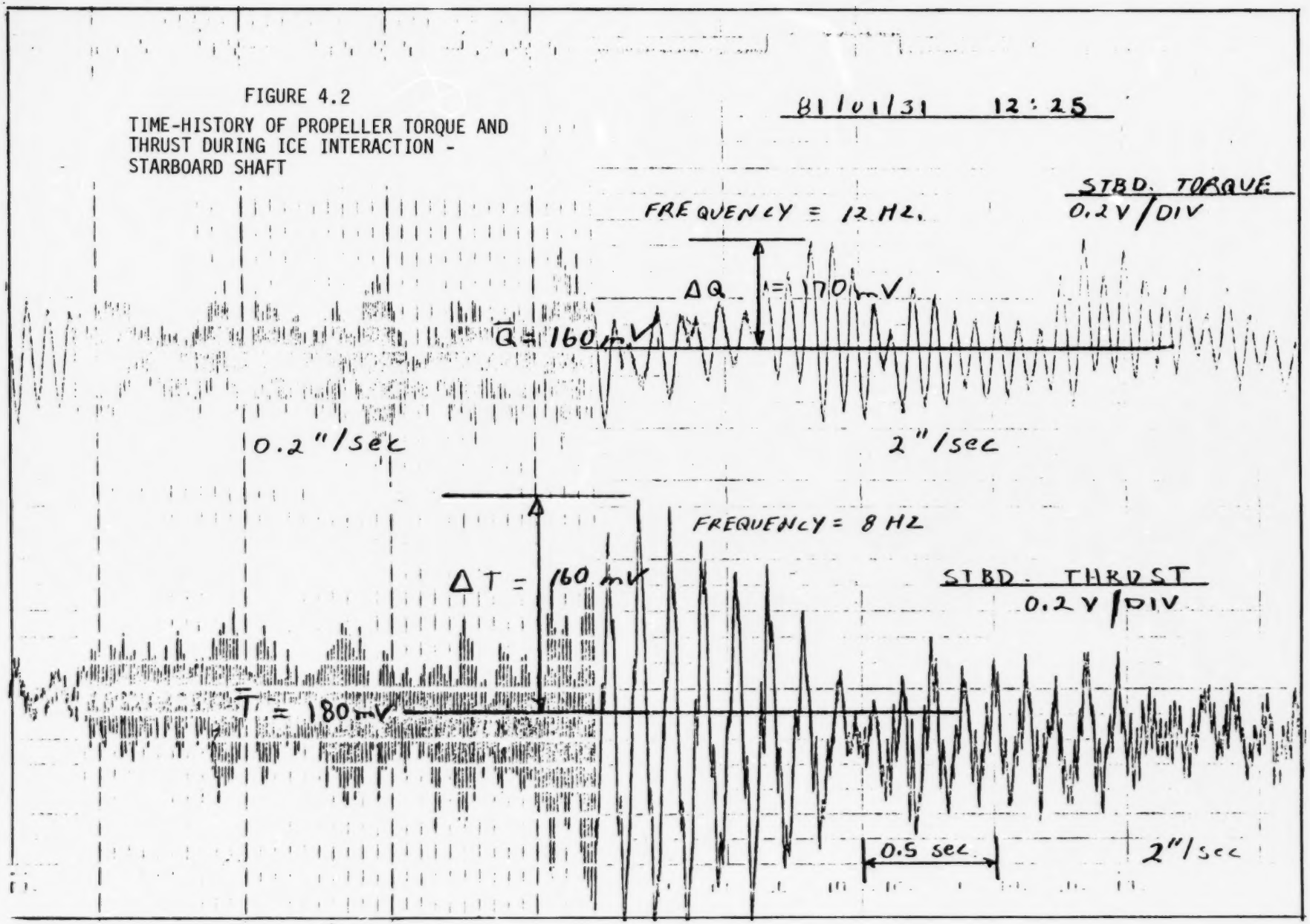
As described in Section 2.1.4 a complete dynamic model of the shaft system was built (see Figure 4.6) and mode shapes and frequencies calculated. The calculated lowest longitudinal natural frequency was 9.43 Hz for the wing shafts and 9.48 Hz for the centreline shaft. The values are within 20% of the measured frequencies from the event studied.

4.3 Ice Loads and Pressures

This data has generally been thoroughly reduced and analyzed, and no additional data from sensors is available. Nevertheless, there are possible alternative data interpretation techniques to the extreme value statistical analysis performed. For example there is more scope for time series analysis. Chevron has spent several years analyzing the time series data, but no knowledge of the information they have deduced is available. Such analysis in conjunction with detailed examination of the overside video record may provide additional information in contact area size, its influence on the load, loading rate and strain rates. While this may yield additional valuable information concerning the ship/ice interaction, it is considered to be a second priority item.

FIGURE 4.2

TIME-HISTORY OF PROPELLER TORQUE AND THRUST DURING ICE INTERACTION - STARBOARD SHAFT



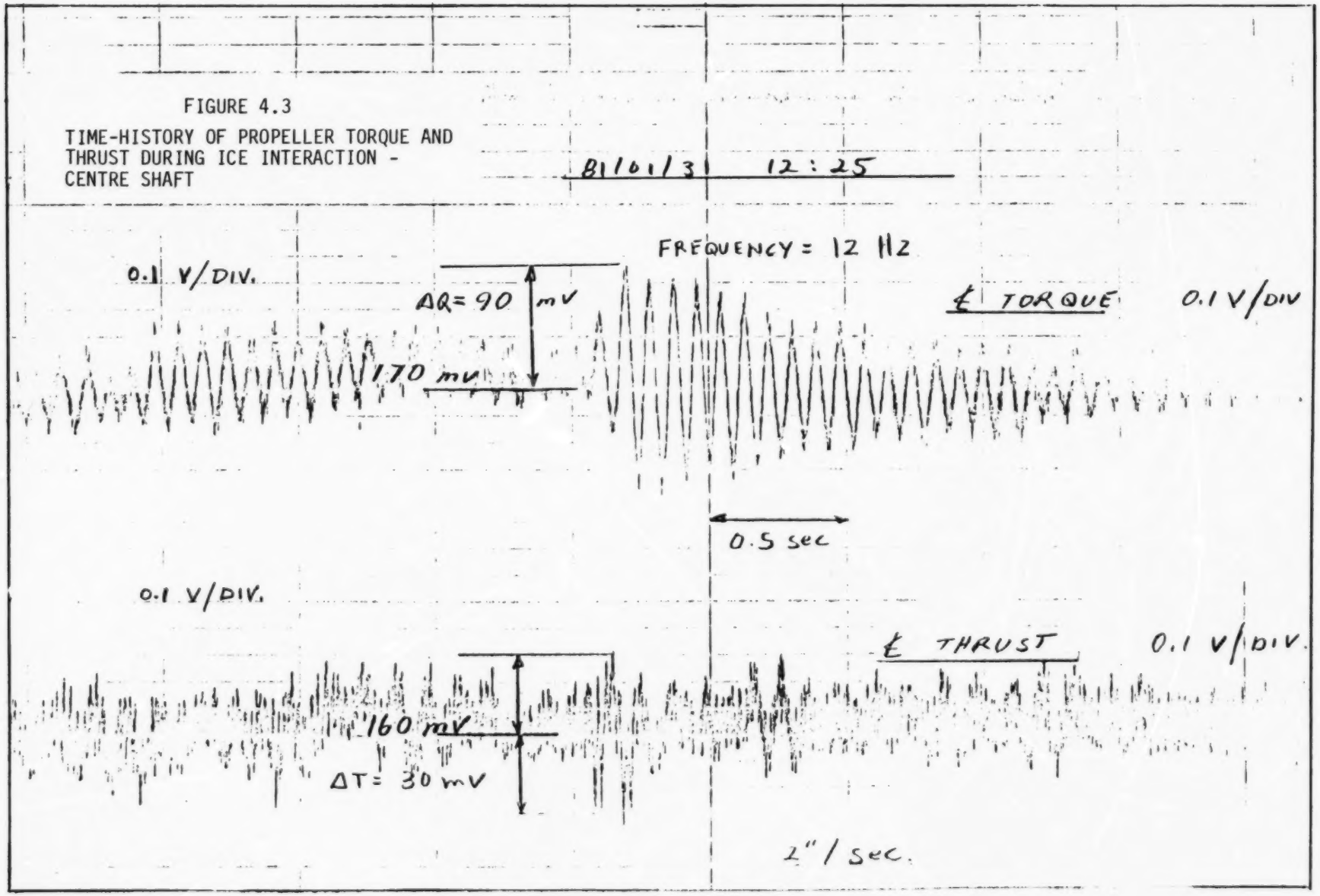


FIGURE 4.3

TIME-HISTORY OF PROPELLER TORQUE AND THRUST DURING ICE INTERACTION - CENTRE SHAFT

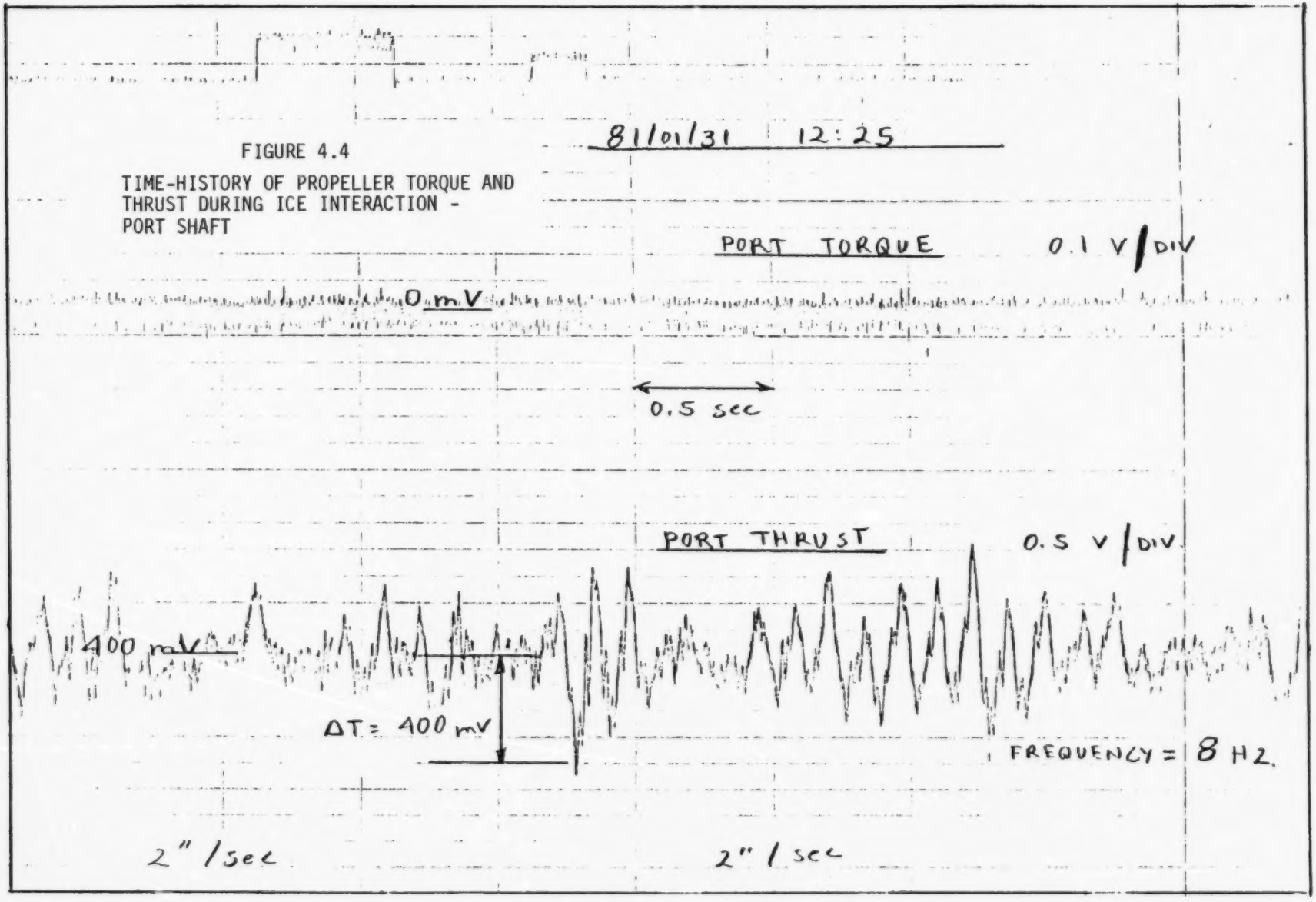


FIGURE 4.4

TIME-HISTORY OF PROPELLER TORQUE AND THRUST DURING ICE INTERACTION - PORT SHAFT

TABLE 4.1

SUMMARY OF SHAFT DATA DURING ICE/PROPELLER INTERACTION

DESCRIPTION	PORT SHAFT	CENTRELINE SHAFT	STARBOARD SHAFT
PERCENT VARIATION FROM MEAN:			
TORQUE	-	28	106
THRUST	100	19	89
FREQUENCY OF VIBRATION (Hz):			
TORQUE	-	12	12
THRUST	8	-	8
DURATION OF ICE/PROPELLER INTERACTION (seconds)	35	none	35
MAXIMUM VARIATION:			
TORQUE	-	17,500 ft.lbs	33,150 ft.lbs
THRUST	30,000 lbs.	3,400 lbs.	19,200 lbs.

DATE/TIME 81/01/31 12:35

OPERATION: BACKING IN LEVEL ICE

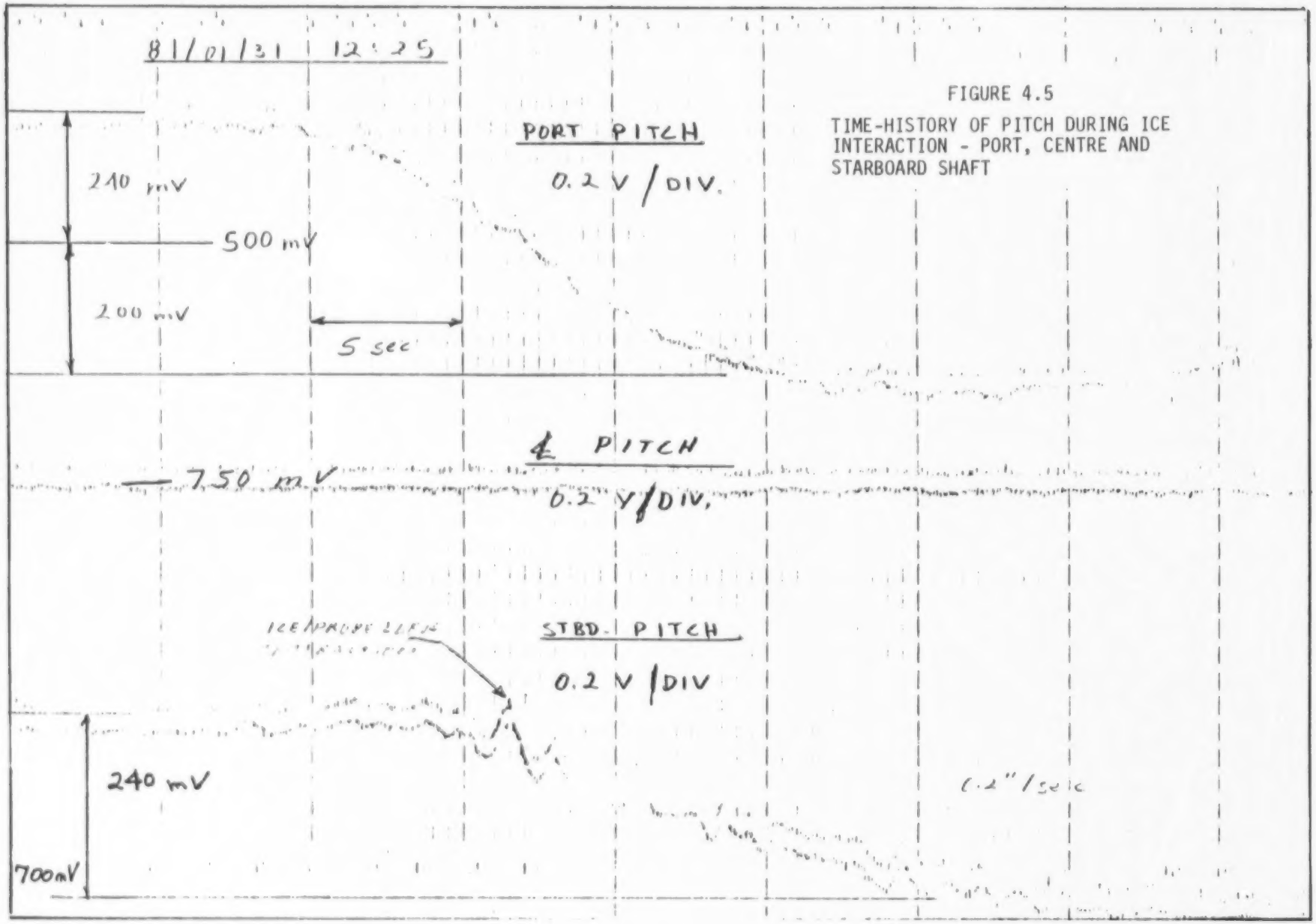
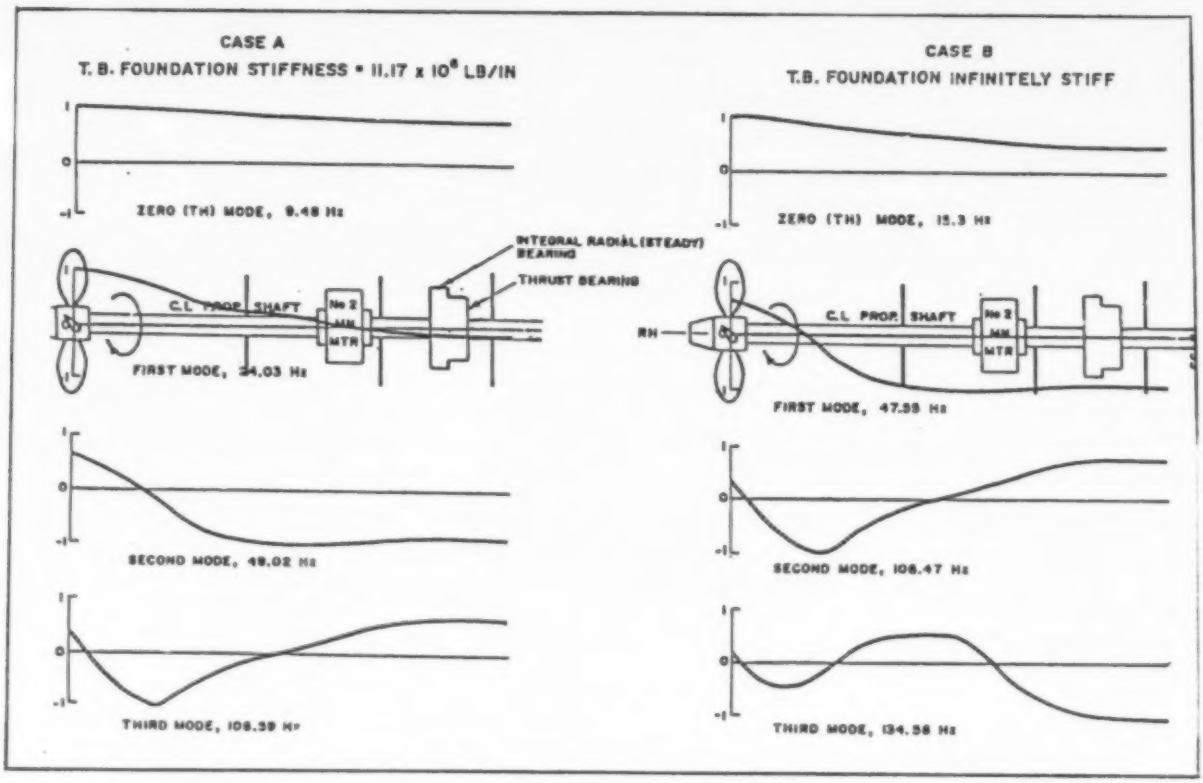


FIGURE 4.5

TIME-HISTORY OF PITCH DURING ICE INTERACTION - PORT, CENTRE AND STARBOARD SHAFT

FIGURE 4.6

MODE SHAPES AND FREQUENCIES FOR
LONGITUDINAL VIBRATION OF PROPULSION SYSTEM
CENTRE SHAFT



4.4 Rudder and Steering Gear Loads

Two sets of recorded data were not analyzed in this program. The first is the output from a triaxial accelerometer mounted on top of the steering gear at the rudder stock. This data would produce 'shock' spectra for the steering gear under all conditions, and would be of value in defining the 'shock environment' for equipment in that location. Comparison of this output with equipment specifications on MIL standards may be of value but is largely of ship specific interest.

The second set of data are strains measured in the steering gear equipment sub-foundation. These measurements were made largely as a follow-up to the failure of the sub-foundation on POLAR STAR. An analysis of the damage had been completed, and the data was thought to be of possible value in assessing the adequacy of the sub-foundation. In conjunction with a Finite Element model of the sub-foundation, information on the design and perhaps the failure mechanisms could be derived. However, this analysis would be ship specific and of little general use.

We therefore recommend that the two sets of data recorded under this project remain catalogued and analyzed only as specific needs arise.

4.5 Manoeuvring Performance

All the measurements made in the Antarctic Manoeuvring Trials have been reduced and analyzed for steady state turning conditions. Analysis of measured parameters during transient manoeuvres, and in particular, examination of the data from the accelerometers which were onboard at the time, correlated to the rudder and heading data may be of use. The motions package onboard during the trials was designed to measure the dynamics of the vessel during level icebreaking, and consisted of measurement of accelerations in three planes at the bow and amidships.

During normal icebreaking operations, use of large rudder angles to manoeuvre the ship to an advantageous icebreaking position, or to hold course was evident, as well as significant lateral accelerations. Some useful relationships may be evident from analysis of this data.

4.6 Video Records

Many hours of video records have been taken during all the aforementioned deployments. This has included masthead video, 'offship' video, over-the-side time lapse video at the structural panel and over the stern.

These video records have in most cases been examined during the data analysis, to assist in identifying cases, and quantifying variables. Nevertheless, it is quite possible that additional information may be gleaned from further review of these tapes.

In addition it is recommended that an edited film be compiled from all the tapes, that will demonstrate the POLAR SEA projects.

4.7 Conclusions and Recommendations for Further Analysis

Project Data Base	Proposed Type of Analysis	Recommended Action
Ship Structural Response	Hull Strain Data - no quality data.	No action
	Deducing propeller milling loads from shaft response - including developing model of shaft further.	Priority 1 as part of future program
	Correlating accelerometer time series data with peak force by developing technique proven on MV ARCTIC - and thus getting Peak Force	Priority 2
Ice Loads and Pressures	Further Analysis of Time Series Data	Priority 2
Rudder and Steering Loads	Accelerometer Data - develop shock spectrum for gear	Priority 2 Ship Specific
	Analyze strain in sub-foundation in conjunction with F.E. model and failure analysis	Priority 3 Ship Specific
Manoeuvring Performance	Analysis of Transient Manoeuvring Data with Analysis of Accelerometer Data	Priority 1

5. REFERENCES

[1] "Winter 1981 Trafficability Tests of the USCGC POLAR SEA, Volume IX: Ice Induced Vibration Measurements and Development of a Model for Icebreaking Excitation Forces" prepared for Transport Canada, Transportation Development Centre by Arctec Canada Limited, Report No. 792C, March 1982. Transport Canada Report TP3617.

[2] "Ice Loads and Ship Response to Ice, USCG Polar Class 1982/83 Deployment", prepared for Transport Canada, Transportation Development Centre by Arctec Canada Limited, Report No. 991C, December 1984. TP6038E

[3] "Antarctic Ice Resistance and Impact Tests Volume II: Impact Tests", prepared for Transport Canada, Transportation Development Centre by Arctec Canada Limited, Report No. 1341C, March 1985. TP7184E

[4] "Arctic Deployment of USCGC Polar Star, Winter 1982 Volume IV: Ice Loads on Steering Gear" prepared for Transport Canada, Transportation Development Centre, Report TP4125E by Arctec Canada Limited, Report No. 937C, September 1982.

[5] Golden, M.E. and Henderson, F.M. "An Updated Guide to the Use of General Bending Response Program (GBRP)", David W. Taylor Naval Ship Research and Development Centre, Report TP 4601, April 1965.

[6] Schlick, O., Series of Articles on Ship Vibrations in Transactions of INA (1884 to 1911).

[7] Nevel, D.E. "A Semi-Infinite Plate on an Elastic Foundation", Cold Regions Research and Engineering Laboratory Report No. 136, March 1965.

[8] Kerr, A.D., "The Bearing Capacity of Floating Ice Plates Subjected to Static or Quasi-Static Loads", Cold Regions Research and Engineering Laboratory Report No. 333, March 1975.

[9] Daley, C.,"Group Four Study, Final Report", prepared for Transport Canada, Coast Guard Northern, Arctec Canada Report No. 1718C.

[10] Arctic Deployment of USCGC POLAR STAR - Winter 1982 Volumes I and III, Arctec Incorporated Report 730B, November 1982.

[11] "Analysis of Ice Load Measurements on USCGC POLAR SEA for years 1982-1984", Arctec Canada Report 1723AC for TDC, February 1986.

[12] "Manoeuvring Tests in Ice Aboard USCGC POLAR STAR in Antarctica 1985", Arctec Canada Report 1723B for TDC, October 1986.

[13] "Study of Steering System Components for Arctic Class Ships", Arctec Canada Report 329C.1 for Canadian Coast Guard, November 1979.

APPENDIX A

INDEX OF POLAR CLASS REPORTS AND SOURCES OF DATA

REPORTS PREPARED BY ARCTEC ENGINEERING LIMITED

MARAD REPORT NO.	AEI REPORT NO.	TITLE
MA-RD-940-79072	500C	Operational Assessment of Commercial Icebreaking Ships in Western Alaskan Water Based on USCGC Polar Class Trafficability (2 Volumes).
	583C	Winter 1981 Trafficability Tests of the USCGC Polar Sea (11 Volumes).
MA-RD-940-83002	730B	Arctic Deployment of USCGC Polar Star - Winter 1982 (6 Volumes).
MA-RD-940-83064	800C	Arctic Deployment of USCGC Polar Sea - Winter 1983 (4 Volumes).
	872C	Level ice Resistance of USCGC Polar Sea in Antarctica 1984 (1 Volume) (prepared for U.S.C.G.).
MA-RD-760-84043	1010C	Bering Sea Data Collection Aboard USCGC Polar Sea, Feb-Mar. 1984 (2 Volumes).
	1060C	Ship Icebreaking Dynamics and Manoeuvring Testing Aboard USCGC in Antarctica (2 Volumes).
	1020C	Beaufort Sea Data Collection and Multi-year Ice Research aboard USCGC Polar Sea Nov/Dec 1984 (1 Volume).

REPORTS PREPARED BY ARCTEC CANADA LIMITED

TRANSPORT CANADA REPORT NO.	ACL REPORT NO.	TITLE
TP 4080E	792C	Winter 1981 Trafficability Tests of the USCGC Polar Sea Volume IX - Ice Induced Vibration Measurement.
TP 4125E	937C	Arctic Deployment of USCGC Polar Star Winter 1982 Volume IV - Ice Loads on Steering Gear Systems.
TP 6038E	991C	Ice Loads and Ship Response to Ice USCGC Polar Class 1982/83 Deployment
TP 7183E	FR1341C.1	Polar Class Antarctic 1984 - Level Ice Resistance Tests.
TP 7184E	FR1341C.2	Polar Class Antarctic 1984 - Ice Impact Tests
	1723AC	Analysis of Ice Load Measurements on USCGC Polar Sea for Years 1982 - 1984
	1723BC	Manoeuvring Tests in Ice Aboard USCGC Polar Star in Antarctica 1985.

DATA

Data Tapes, video tapes and data discs containing raw data are currently stored at Arctec Canada Limited and Arctec Engineering, Inc., Columbia for the U.S. and Canadian projects respectively.